2001 Mars Odyssey

RELAY DATA SERVICE

REV. A

April, 2001

JPL D-19591
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Jet Propulsion Laboratory
California Institute of Technology

2001 MARS ODYSSEY

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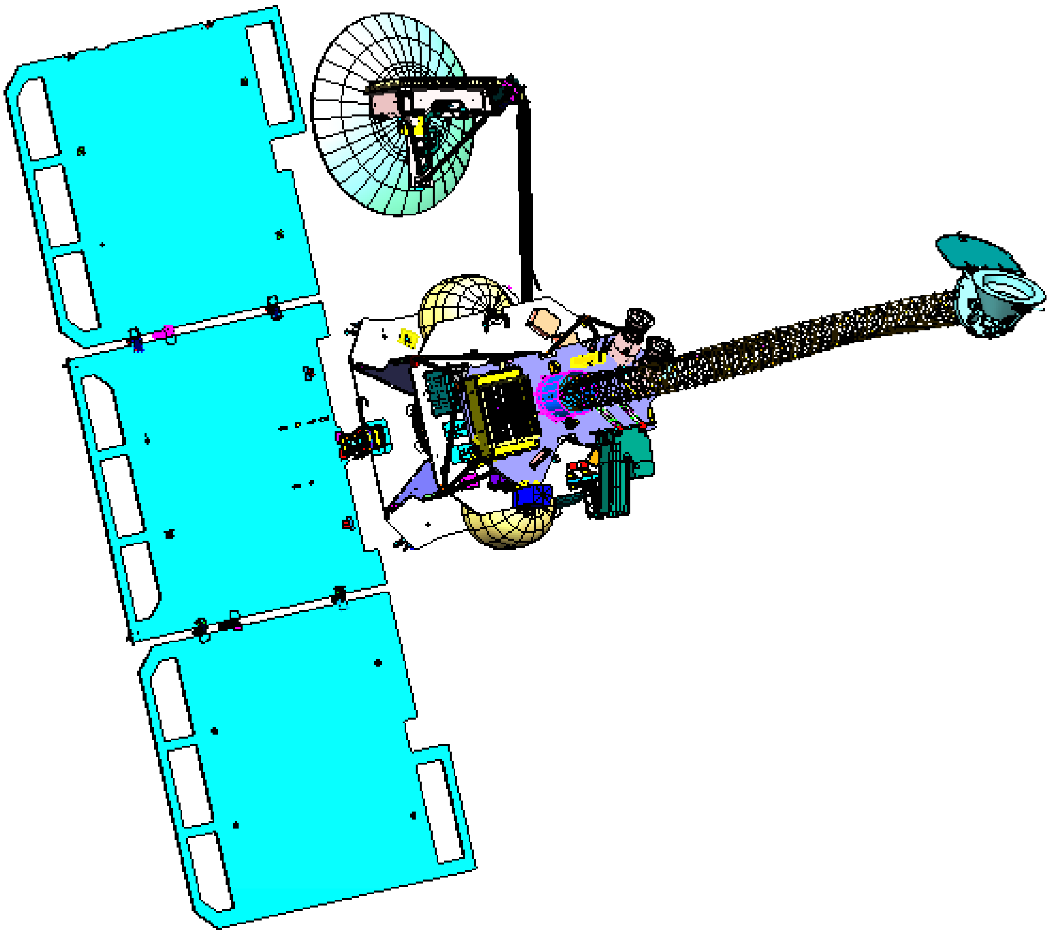

JPL D-19591, Project Document 722-803

Prepared by: Andrea Barbieri

Rev. A - April 2001

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1 Introduction

This document describes the relay service provided by the 2001 Mars Odyssey Orbiter to future mission on Mars (referred as Surface Elements, SE). The content of this document is part of the mission Telecommunications System Operations Handbook[1], but it's presented in this form as a quick reference source of information to the relay system.

The main objectives of this document are:

1. give an overview of the on-board processing of relay data with a particular attention to explain the consequences to the end to end data flow design
2. document the implementation of the Proximity Link Standard by the Orbiter, highlighting the deviations from it
3. provide the parameters necessary to perform link budget with the Mars Surveyor Project (MSP) 2001 Orbiter.

A separate Interface Control Document between each user and the MSP'01 project shall be developed in order to detail the communications interface.

In this document orbiter refers to the MSP'01 orbiter, *Return Link* refers to the transfer of data from the SE to the ground through the orbiter. *Forward Link* is the opposite direction of the data flow. We refer to the SE-orbiter link as *Proximity Link* and to the orbiter-ground link as *Deep Space Link.*

The following individuals contributed to the information and the review of this document and their support is greatly appreciated:

- at JPL Stan Butman, Andre Makovsky and Arv Vaisnys
- at LMA Chris Gadda, Gina Signori and Jeff Smernoff
- at Cincinnati Electronics Doug Mertz.

[1] JPL D-19591, PD 722-802, version 3, March 2000.

2 Orbiter On-Board Processing of Relay Data and Deep Space Link

This section will give an overview on how the orbiter processes the relay data and transmits/receives them in the deep space link[2]. The first section is an introduction on the spacecraft components involved in the flow of relay data in the orbiter. Then it will be shown how commands to a Surface Element (SE) must be sent from the Deep Space Network (DSN) to the orbiter in order to be successfully relayed to the SE (forward link). The last section of the section - return link - explains how the data coming from the Orbiter UHF Radio are processed on-board and the resulting consequences on the SE data management design. The proximity link, subject of Section 3 of this document, will be considered transparent in this section.

Sections 2.1-2.3 describe the on-board handling of relay data as implemented in flight software at the time of this document. An Engineering Change Request (ECR) has been approved by the project and it will patch the software to add new functionalities - this ECR is briefly described in Section 2.4.

2.1 Overview

Figure 1 illustrates the components involved in the data flow of relay data in the orbiter.

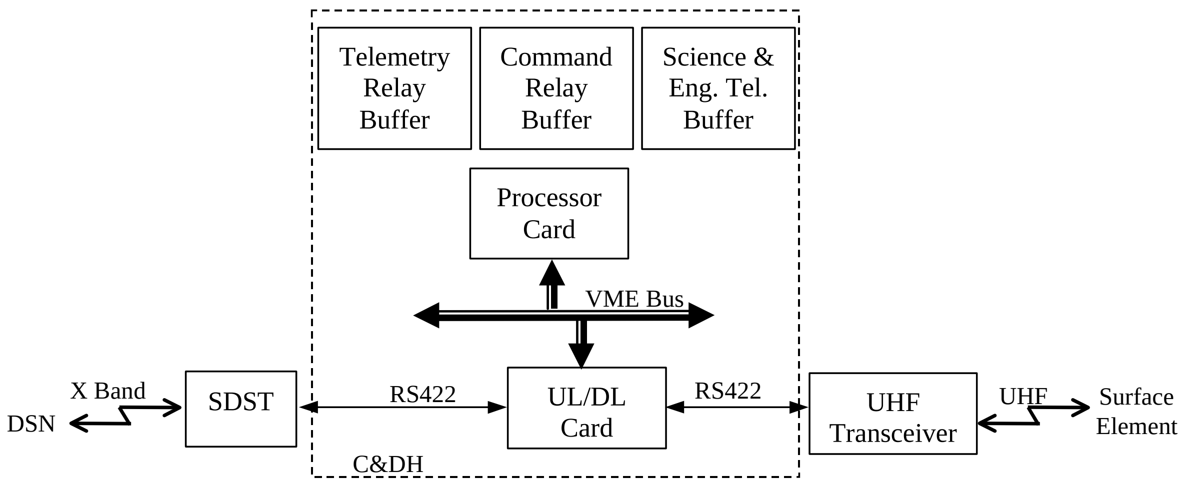

Figure 1. Relay Data Flow in the Orbiter

The UHF transceiver is the terminal for RF communications with the SE and it also implements the Proximity-1 Link protocol that will be explained in detail in Section 3. The transceiver has a temporary data storage, with a 128 kbyte FIFO divided between the transmitting and receiving functions.

The interface between the transceiver and the flight computer is a particular device called ULDL (Uplink/Downlink) card, which has its own FIFO.

The relay data is stored in a particular segment of the orbiter memory, called Relay Buffer, logically separated from other orbiter data (science measurement, engineering telemetry or commands). The size allocation of the relay buffer has to be shared with the buffers that contain orbiter data. The size of the

[2] Mars Odyssey Telemetry and Command Dictionaries, JPL D-2047 and D-2048, March 2001

buffer is configurable and controlled by the last initialization of the DWN_PCKT_BUFFER flight software object.

Communications with the ground will use X band via the Small Deep Space Transponder (SDST). The ULDL card is also the interface between the computer and the transponder.

The orbiter can be commanded in one of three *Downlink Modes*:

1. *Relay Command*: transmission at UHF of relay commands from the orbiter to the SE on Mars
2. *Nominal Telemetry*: transmission at X band of orbiter (engineering or science) data to the ground
3. *Relay Telemetry*: transmission at X band of SE data to the ground.

Given the fact that the interface between the Command and Data Handling (C&DH) subsystem and the UHF and X band radios is unique, only one of this mode can be used at any time.

In the same way there are *Uplink Modes*, where the orbiter receives data:

1. *UHF Telemetry*: reception of UHF telemetry data from the SE
2. *X Band Command*: reception of X band commands from the ground; the virtual channel number in the received transfer frame header will distinguish between commands intended for the orbiter and commands for the SE.

It must be noted that even in *UHF Telemetry Mode* the orbiter will be able to receive a particular type of X band commands, called hardware commands, that are executed directly by the ULDL card by-passing the flight software.

2.2 Forward Link

The uplink from the ground to the MSP'01 Orbiter follows the CCSDS recommendations 202.0-B-2 and 201.0-B-1 for the telecommand service.

At the frame layer level, the lander command data is formatted in transfer frames composed by a 40-bit header, up to 1984 bits of data (called command message) followed by 16 bits of Frame Error Control Word (FECW). The 40-bit header is composed by the following fields:

- first six bits are '001000'
- 10 bits for spacecraft ID, with value '35'h[3] identifying the MSP'01 orbiter
- 6 bits of Virtual Channel (VC) ID. VC ID is used to distinguish the type of command message. In particular VC ID equal to 6 identifies that the command message is intended for the Surface Element (SE)
- the next 8 bits are for transfer frame length in bytes. The value given is the number of bytes minus 1 with a maximum value of 255 (indicating 256 bytes long). The length includes the 40 bits (5 bytes) of frame header and the 16 bits (2 bytes) of FECW
- The last 8 bits are the command transfer frame sequence number. Out of sequence transfer frames are not executed by Flight Software, but stored until the frame with the right sequence number is received.

At the coding layer, the transfer frames are divided in 56-bit long blocks, then BCH encoded into 64-bit data units called code-blocks. In this level the signal sent from the ground to the orbiter consists of the following fields:

[3] the h denotes a number in hexadecimal notation.

- 176 bits of alternating 1's and 0's. This *acquisition sequence* helps to ensure that the Command Detector Unit (CDU) in the SDST will achieve bit synchronization
- A 16-bit command start word, either 'EB90'h or '146F'h[4] - this *start sequence* delineates the start of the code-blocks
- A series of 64-bit *code-blocks*. Each code-block has 56 bits of command data, 7 bits for error detection and correction (EDAC) and 1 fill bit (always a 0). There are from 1 to 37 code blocks
- After the last code-block, there is a *tail seque*nce: 64 bits of alternating 1's and 0's
- An *idle sequence*, which is an unlimited number of alternating 1's and 0's.

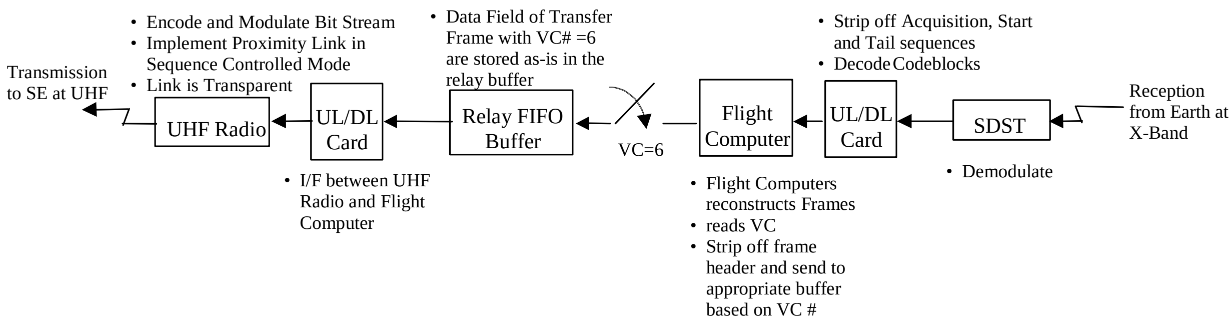

Figure 2. Orbiter: Data Flow in the Forward Link

Figure 3 presents the data flow of the command data through the orbiter.

During an uplink session the SDST acquires, tracks and demodulates the RF signal to baseband and passes the bit stream to the Hardware Command Decoder (HCD) in the ULDL (Uplink/Downlink) card which will strip off the acquisition, start and tail sequences and pass the decoded code-blocks to the computer. Flight Software takes the 56 bits of data (out of 64) of each code-block and re-builds the command transfer frames.

As explained above if the Virtual Channel ID for the transfer frame is equal to 6[5], then the command message (transfer frame without header and FECW) is intended for the SE and is passed unaltered to a FIFO, called Command Relay Buffer, in the same bit order as it was received by the orbiter. A special counter *RLY_CBUF_USE* will increment while data is transferred to the relay buffer.

Once commanded from the ground (*Downlink Mode* = *Relay Command*) the orbiter will establish communications with the SE. The ULDL card will take data from the Command Relay Buffer and transfer them to the transmitting FIFO of the UHF transceiver. In order not to overflow this buffer, its size is monitored: when it’s less than half full (32768 bytes) the transfer rate is 248 kbps, otherwise 5 bps. The transceiver will transmit the command data over the proximity link as explained in detail in section 3.

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[4] The 2 versions are complements of each other, since the CDU may lock up on either a positive polarity (then it's EB90h) or 146Fh. This 180-degree ambiguity is a feature of BPSK demodulators.

[5] reception of VC ID 6 frames by the orbiter will increment the counters VC6_PACK_VALID and VC6_PACK_INV and can be verified in the engineering telemetry.

It must be noted that even when the flight software is not pushing command data in the forward link, the ULDL card (that cannot be stopped) inserts "unpredictable" bits into the transceiver buffer (if powered on) at 5 bps. This will happen typically at the beginning and at the end of a relay pass or when there is no data at all to send in the forward link. The SE must filter out of these unpredictable bits at the beginning and at the end of a pass.

Note that if the Downlink Mode is switched to *Nominal* or *Relay Telemetry* the commands on the relay buffer will be deleted This can happen for example if at the end of a relay pass over a SE the command buffer is not empty and the orbiter communicates with the ground (to transfer either its own data or SE telemetry). In this case the command session has to start over with mission operations on the ground uploading again to the orbiter the relay commands lost. In addition when the Command Relay buffer is emptied the flight software will insert a particular file. This file, called *autoswitch.dat*, is intended to enable a block in the lander that commands to stop accepting command data in the relay link[6].

The MSP'01 orbiter implementation does not impose any constraint on the content of the command transfer frame that will be transferred as-is without processing in the proximity link. The appropriate interface between the SE project and MSOO/TMOD will allow the insertion of SE commands into the data field of the command transfer frames according to the CCSDS standard, but with VC ID equal to 6 and orbiter S/C ID. The implementation of the coding layer (sequences and code-blocks as explained) and the transmission into the forward deep space link will be done by MSOO/TMOD.

Note that since the relay buffer follows the FIFO rule there is no way to prioritize forwarding of commands between multiple users.

Finally Figure 4 summarizes the end to end data flow from the ground to the SE. Considering the proximity link to be transparent, commands will be received by the SE as intended.

[6] this was designed to signal the end of the transmission before the unpredictable bits inserted by the ULDL card - this file is optional and configurable.

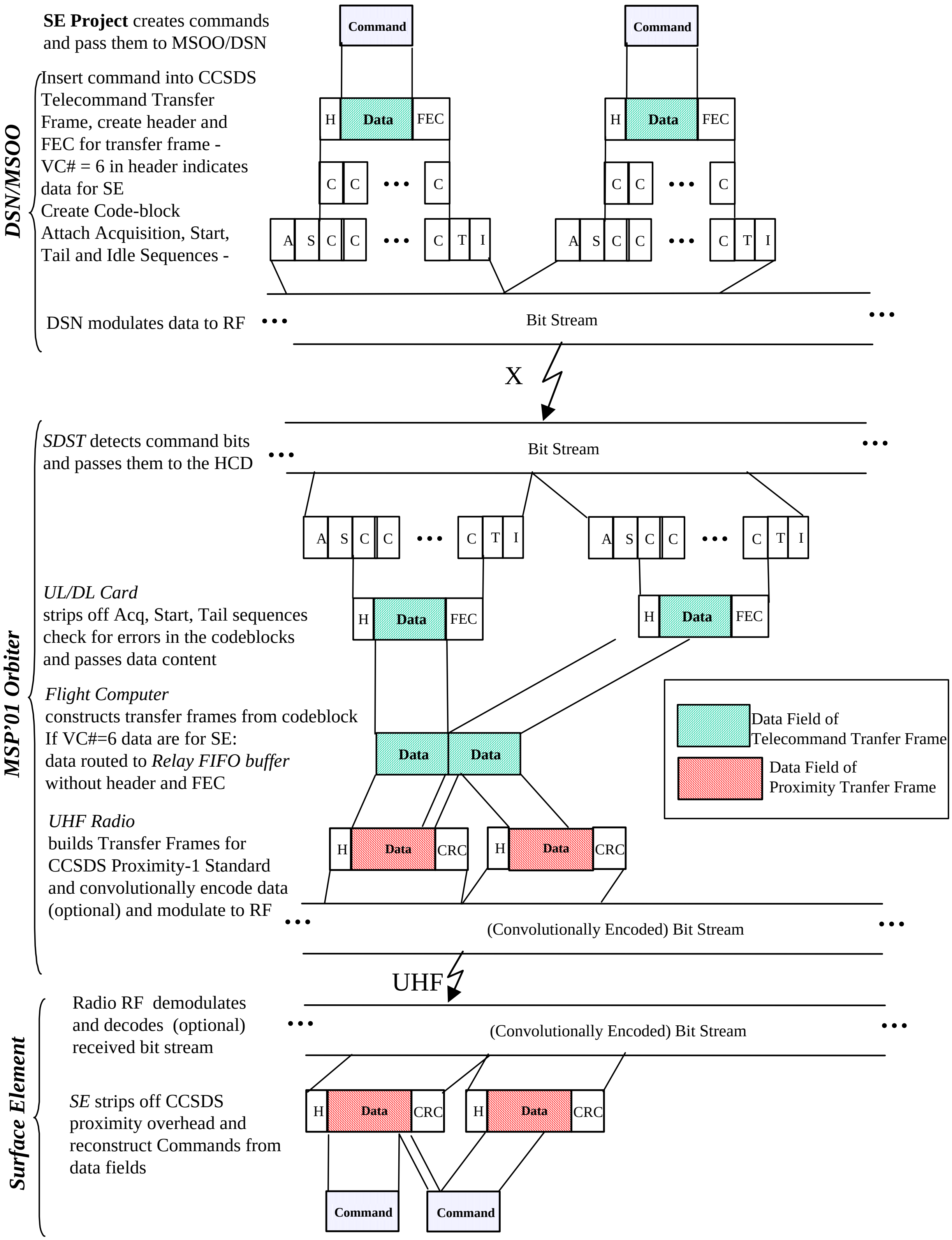

Figure 3. Command Flow from the DSN to SE

2.3 Return Link

The flow in the orbiter of the return link data is illustrated in Figure 5.

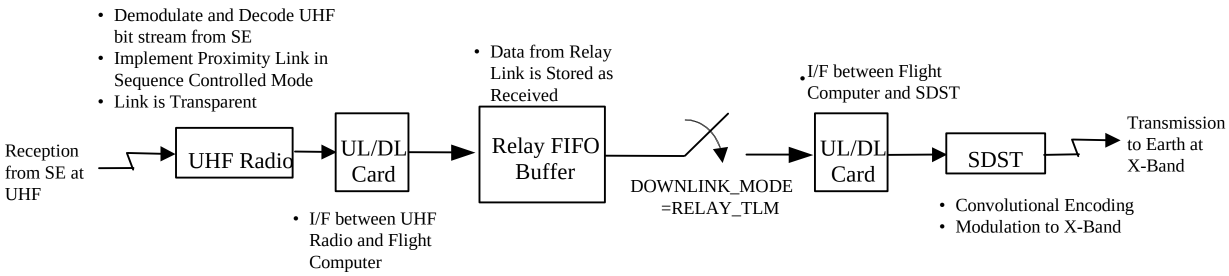

Figure 4. Orbiter: Data Flow in the Return Link

After the relay link is established, the UHF transceiver will demodulate and convolutionally decode (optional) the received signal. The data is then routed through the ULDL card into a special buffer, called Telemetry Relay Buffer, in the flight computer DRAM. A special counter, *RLY_TBUF_USE*, will increment while data is filling this buffer and no processing of any kind is performed on its content.

When a ground station communication pass is scheduled and the transmission of relay data is desired the flight software is commanded to *Relay Telemetry* mode using the *Downlink Mode* command. This command will stop the downlink of the orbiter's own data, if any, and the bits will start flowing with a First In First Out (FIFO) rule from the Telemetry Relay Buffer to the Small Deep Space Transponder (SDST). Here the data is convolutionally encoded, modulated at X band and transmitted to the ground.

If the relay buffer is empty while in the *Relay Telemetry* mode, flight software will insert virtual fill frames in the downlink until data is added to the relay buffer or the *Downlink Mode* is switched to any other mode.

If the buffer was empty when the last telemetry session was stopped, then FSW will start a the beginning of the pass when commanded in Relay Telemetry mode. Note that when switching between orbiter data and SE data , frame lock might be lost at the DSN. The bit stream coming from the SE should have some prepended pad (approximately 6 telemetry transfer frames) to avoid the loss of useful data.

If the buffer was not empty when the last relay downlink session was stopped, the flight software will transmit the last 8160 bytes (this number assures the transfer of at least 4 telemetry transfer frames that are each 1264 bytes long for standard multi-mission operations[7]). The downlink of relay telemetry stops when the *Downlink Mode* is commanded to anything but *Relay Telemetry*.

It should be clear that the processing of return data by the MSP'01 orbiter is just a *store and forward* process. Since the transmission from the orbiter to the ground has to follow the CCSDS Recommendation on Packet Telemetry to be compatible with the ground system, it follows that the SE has to implement its own data formatting in order to be compatible with the recommendation[8]. The SE needs to:

- construct a telemetry transfer frame including in the header its own S/C ID

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[7] See Appendix B for a description of the orbiter telemetry transfer frame format.

[8] CCSDS 102.0-B-2 and subsequent versions. The particular version does not concern the Orbiter, but has to be agreed by the SE and TMOD/MSOO.

- employ one of two types of encoding to protect the data
  1. Reed Solomon with interleaving depth 1 (short frame) or depth 5 (long frame) or
  2. Perform Forward Error Coding
- Insert the Attached Synchronization Marker (ASM) at the beginning at the transfer frame.

Once the ground receiver demodulates and convolutionally decodes the X band downlink the data will look as if coming directly from the SE element since there is a stream of telemetry transfer frames with the SE S/C ID.

It must be noted that the orbiter deep space link is designed (from the input of the SDST to the output of the DSN decoder) for a BER of 5.0E-3. This will results in a negligible Frame Error Rate (FER) if the Reed Solomon encoding is employed since it's capable of correcting frames. If the SE project decides to implement the Forward Error Control approach the ground system (DSN or the surface element mission operations) will detect a considerable amount of frames in error (the FER will be a function of the frame length) unless the link margin is increased in the deep space link (for example decreasing the bit rate by a factor 1.7, will increase the SNR by 2.2 dB, allowing a BER of approximately 1.0E-5).

Other two consequences of the store and forward approach have to be kept in mind:

1. In the case that a transfer frame is received with errors (FEC coding) or with too many errors (R/S encoding) in the deep space link, the request for re-transmission must be sent to the SE via orbiter since the orbiter did not keep the data in its relay buffer
2. If the relay buffer contains data from multiple users, there is no way to prioritize downlink transmission, since it's first arrived-first downlinked service (FIFO).

The data flow from the SE, starting with the source packets created by each application, to the ground is illustrated in Figure 6. At the ground the telemetry source packets received by TMOD/MSOO will be routed to the SE project through the negotiated interface.

2.4 Planned Modifications to Relay Software

Two ECR's[9] have been submitted to the Odyssey Project to streamline the on-board processing of relay data and to add the support for multiple landed elements. The flight software will be patched after Mars orbit insertion, but these changes will have to be tested.

In the forward link the change will allow the capability of having commands for multiple SEs ready to be relayed to Mars.

In the return link data coming from the SE will be formatted by the orbiter FSW into source packets with a fixed length (1024 bytes, TBC). The APID of these packets (up to 4) will be used to distinguish between SE. These packets will then be subject to the same rules (prioritization, aging, …) as the other orbiter science and engineering data. In addition the orbiter can now insert these packets with SE data into telemetry transfer frames including the Reed Solomon data.

The main advantages of these approach are that the SE does not have to implement the telemetry frame structure, saving approximately 13% overhead in the proximity link due to Reed Solomon overhead, and the ability of prioritizing downlink between different SE sets of data and to have orbiter engineering telemetry interleaved with SE data.

[9] MSP'01 Project ECR #84A and #98

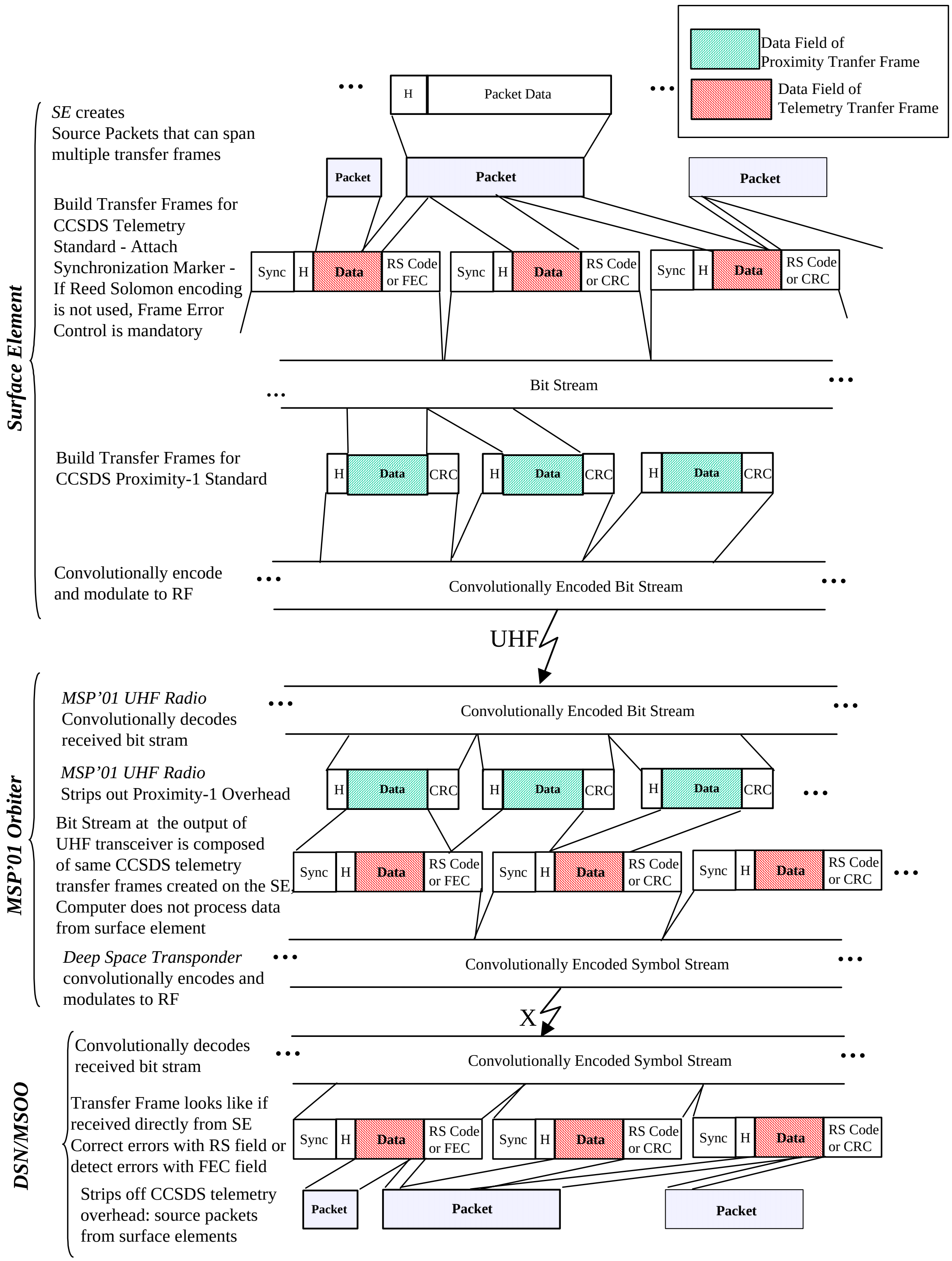

Figure 5. Telemetry Flow from SE to DSN

3 Proximity Link: Orbiter - Surface Element

3.1 Orbiter Implementation of Proximity-1 Space Link Protocol

The orbiter implements the CCSDS draft recommendations for the Proximity-1 Space Link Protocol[10] with few exceptions. This section will highlight the specific implementation of the protocol (not all the modes envisioned are implemented) with the non-conformities and it will specify additional features.

3.1.1 Physical Layer

The following is a list of parameters corresponding to the CCSDS recommendation.

- Frequency:
  - Single forward frequency at 437.1 MHz
  - Single return frequency at 401.585625 MHz
- RHCP (Right Hand Circular Polarization) for the forward and return link
- PCM/Bi-Phase-L/PM modulation with residual carrier provided with a modulation of 1.05 radians (60°)
- Data Rates:
  - forward link: 8, 32, 128, 256 kbps
  - return link: 8, 32, 128, 256 kbps
- Convolutional coding and decoding:
  - convolutional encoding with rate 1/2 and constraint length 7 as defined in the block diagram below. Note that the orbiter does not implement the inversion of the G2 polynomial as specified in the recommendation
  - convolutional decoding with 3-bit soft quantization
  - option of by-passing the convolutional coding/decoding (G2 vector not inverted)

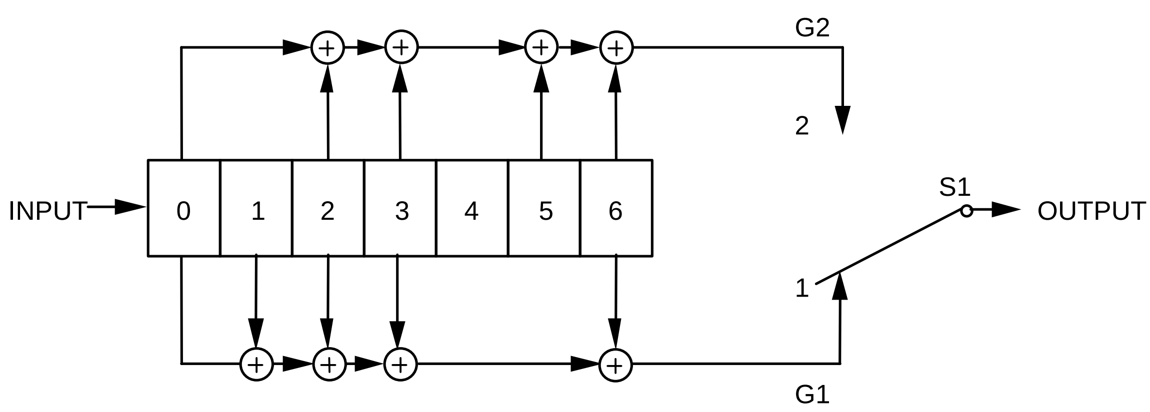

Figure 6. Block Diagram of Convolutional Encoder

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[10] Proximity-1 Space Link Protocol, CCSDS 211.0-R-2, January 2000.

The following features are provided by the MSP'01 orbiter, but not specified in the CCSDS recommendation:

- FSK NRZ-L modulation with the following data rates:
  - forward link: 8 kbps uncoded
  - return link: 8, 128 kbps uncoded
  - FSK transmission can be scrambled or not
- CW Transmission (to trigger micro-probes) at the following frequencies:
  - 437.1, 440.7425, 444.38 and 448.0275 MHz.

3.1.2 Frame Layer

This section will describe the frame layer that provides the structure (sequencing and forward error detection) that allows the establishment of a compatible link and the exchange of error free information between the orbiter and the surface element. It also allows verification that the orbiter is communicating with the intended SE.

Proximity Link Transfer Unit (PLTU)

As specified in the recommendation the PLTU is composed of:

- an Attached Synchronization Marker (ASM) composed by 24 bits defined as 'FAF320' in hexadecimal notation
- a *Transfer Frame* as described below
- an attached CRC (Cyclic Redundancy Code) calculated on the transfer frame (header and data field) with the following generator polynomial:

$$x^{32}+ x^{23}+ x^{21}+ x^{11}+ x^{2}+1$$

Transfer Frame

The transfer frame is composed of 5 bytes of header followed by a data field with 1 to 1019 bytes. The header is composed by 10 fields as described below (see Figure 8 for an illustration of the PLTU and Transfer Frame Format):

PLTU	*ASM*	*Transfer Frame*	*CRC*
	3 bytes	up to 1024 bytes	4 bytes

Transfer Frame	*Header*	*Data Field*
	5 bytes	up to 1019 bytes

Header	*Version Number*	*QoS*	*PDU Type ID*	*Data Field Construction ID*	*S/C ID*	*VC ID*	*Port ID*	*Source Destination Flag*	*Frame Length*	*Frame Sequence Number*
bits	0,1	2	3	4, 5	6-15	16	17-19	20	21-31	32-39

Figure 7. Format of the Proximity Link Transfer Unit, of the Transfer Frame and its Header

- Transfer Frame Version Number. Bits 0,1 contain the binary value '10'
- Quality of Service (QoS) Indicator, bit 2:
  - '0' specifies that the frame is a Sequence Controlled Transfer Frame (this mode is also called "reliable bit stream") - the acceptance of the frame is subject to the CRC check, S/C ID[11] and frame sequence number validation (see frame length field description). Retransmission is requested in case of failed CRC
  - '1' indicates that the transfer frame is an Expedited Transfer Frame (this mode is also called "message-by pass") - the acceptance of the frame is subject to the CRC check
- Protocol Data Unit (PDU) Type ID. Bit 3, if:
  - '0' indicates that the data fields contains User Data
  - '1' specifies that the data field contains control information for the proximity link (see the following section, External PDU).

The following table summarize the mode corresponding to the setting of the QoS and PDU Type ID fields.

Table 1. QoS and PDU Type ID Fields vs. transmitting mode

QoS	***PDU Type ID***	**Mode**
0	0	User Data / Sequence Controlled (Reliable Bit Stream)
0	1	Reserved
1	0	User Data / Expedite Transfer (Message-by-pass)
1	1	PLCW (ACK/NACK) or Directive PDU

In the User Data/Sequence Controlled Mode, the data field of the transfer frame contains user data that will be sent in a sequence controlled mode over the link; this mode will be described in Section 3.1.3. In the User Data/Expedite Mode the content is still user data, but the received frame is subject only to CRC check and acknowledgments are not exchanged in the link; this mode will be briefly described in Section 3.1.4. When Bits 2 and 3 of the header are '11' the frame contains either the ACK/NACK (called PLCW, Proximity Link Control Word in the standard) of the sequence controlled service or Directives that are used to configure transceivers at the two ends of the link in a compatible mode; they will be described later in the section and they are collectively referred as External PDU.

[11] the S/C ID check should be enabled, according to the standard, by the Source or Destination Flag field. See the description of this field in the next page.

- Data Field Construction ID. Bits 4 and 5
  - orbiter always transmit '11' (corresponding to User Defined Data in the protocol language)
  - don't care in reception
- Spacecraft (S/C) ID. 10 bits that identify the S/C which is either the source or the destination of the data contained in the transfer frame, see also the Source or Destination Flag field. The orbiter flight software will always load the ID of the surface elements it wants to communicate with, it will verify that incoming frames have the loaded S/C ID and it will transmit frames with the same ID
- Virtual Channel ID. One bit always
  - '0' is always transmitted by the orbiter indicating no virtual channel support
  - don't care in reception
- Port ID. Three bits:
  - orbiter always transmit '000' indicating no support for multiple logical or physical connection port
  - don't care in reception
- Source or Destination Flag, bit 20, with the following definition:
  - '0', the S/C ID field contains the source of the transfer frame
  - '1' the S/C ID field contains the destination of the transfer frame

  Since the S/C ID will be always the SE ID, the value '0' will be in the frames received by the orbiter, '1' will be in the transmitted frames. In addition it must be noted that when the orbiter receives a frame with this flag set to Source and the QoS bit is '0', it performs the test of the S/C ID not following the Proximity Standard
- Frame Length. 11 bits indicating the length of the transfer frame in bytes minus 1
- Frame Sequence Number. 8 bits indicating the frame number, incremented when the QoS indicator is '1' (sequence controlled). The counter rolls-over when reaching the value 255.

Set Directives and PLCW [External Protocol Data Units]

As explained before when the combination of the QoS indicator and the PDU Type is '11' the content of the transfer frame data field carries a control directive or a report on the status of the sequence controlled service. Two types of PDU are used by the orbiter and distinguished by the first 2 bits of the data field (PDU Type)

a. Directive PDU

In Figure 8, PDU Type = '00' indicates a Directive or Report Data Unit. The orbiter uses only the Directive PDU which is flagged by the next two bits being '00' (PDU Sub-type field), see Figure 9, and is used to configure the SE transceiver in a compatible mode with the orbiter[12]. The Length field, in the orbiter implementation, is fixed at '0100' indicating that the directive contains 4 bytes, with the first 2 bytes reserved for a Set Transmitter directive and the last 2 for a Set Receiver Directive.

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[12] Since the MSP'01 always initiates the link with the SE, the Directive PDU is always sent by the Orbiter to the SE.

	ASM	*Header*	*Data Field*	*CRC*
Directive PDU	3 bytes	5 bytes	5 bytes	4 bytes

	PDU Type	*PDU Subtype*	*Length*	*Set TX Directive*	*Set RX Directive*
Data Field, bits	0,1='00'	2,3='00'	4-7='0100'	8-23	24-39

Figure 8. Directive PDU

The Set Transmitter and Receiver directives have a common structure as shown in the following Figure, where the specific commands (set mode, data rate, …) will be effective on the receiver or transmitter portion of the SE based on the 3 bits of the Directive Type field (bits 13-15): '000' indicates a Set Transmitter directive, '010' a Set Receiver directive.

Mode	*Rate*	*Modulation*	*Encoding*	*Frequency*	*Directive Type*
0,1,2	3,4,5	6,7	8,9	10,11,12='000'	13,14,15

Figure 9. Set Receiver and Transmitter Directive

The Frequency field is always set to '000' by the orbiter since MSP'01 does not support multiple frequencies (in reception the orbiter does not check the content of this field). The following two Tables will help to decode the setting of parameters based on the value of bits 0-9 in the Set Directive.

Table 2. Set TX Directive Sent by the Orbiter to the SE

TX Mode	**TX Data Rate**	**TX Modulation**	**TX Coding**
000=Standby	000=8 KBPS	00=FSK	00=Scramble
001=Sequence Controlled (Reliable Bit-Stream)	001=32 KBPS	01=PSK	01=Viterbi/ Convolutional
010=Expedited Frame (Message Bypass)	010=128 KBPS	10=PSK Coherent	10=Bypass Coding
011=Unreliable Bit Stream	011=256 KBPS		
100=Tone Beacon(*)			
101=Canister Mode			

(*) in this mode the orbiter receiver will go into stand-by - this mode is intended to set the SE to transmit a tone for Doppler measurements with an higher SNR

Table 3. Set RX Directive Sent by the Orbiter to the SE

RX Mode	RX Data Rate	RX Modulation	RX Coding
000=Standby	000=8 KBPS	00=FSK	00=Scramble
001=Sequence Controlled (Reliable Bit-Stream)	001=32 KBPS		01=Viterbi/ Convolutional
010=Expedited Frame (Message Bypass)	010=128 KBPS	10=PSK Coherent (*)	10=Bypass Coding
011=Unreliable Bit Stream	011=256 KBPS		
100=Tone Beacon			

(*) PSK coherent shall be the same as PSK non-coherent for the receiving section

Note that in the MSP'01 implementation 3 bits are reserved for the data rate and 2 for the modulation. Instead the Proximity standard specifies 4 bits for the data rate and 1 for the modulation (switching between PSK and PSK coherent). Later on it will be explained how to set the bits 3-7 in the Set Transmitter and Set Receiver directives for compatibility between the standard and the orbiter.

The orbiter transceiver will configure its transmitter and receiver sections in a compatible mode respectively with the Set Receiver and Set Transmitter directives.

The Surface Elements that follows the Proximity-1 protocol will need to use the following definitions of the Data Rate field and Modulation field (bits 3-7 of the Set TX/RX directive), when receiving a Directive PDU from the orbiter:

'00010' = 8 kbps PSK coherent '00001' = 8 kbps non-coherent

'00110' = 32 kbps PSK coherent '00101' = 32 kbps non-coherent

'01010' = 128 kbps PSK coherent '01001' = 128 kbps non-coherent

'01110' = 256 kbps PSK coherent '01101' = 256 kbps non-coherent.

In addition it's worthwhile repeating again that the convolutional code supported is without the vector G2 inverted and is specified with the bits 8-9 of the Directive field being '01'.

b. Proximity Link Control Word (PLCW)

PDU Type = '10', in Figure 8, indicates a PLCW used to transmit over the link the status of the Sequence Controlled Service. The data field contains two bytes and its structure is shown in the following Figure and explained below:

	ASM	*Header*	*Data Field*	*CRC*
PLCW	3 bytes	5 bytes	2 bytes	4 bytes

	PDU Type	*Retransmit Flag*	*VC ID*	*Spare*	*Expedited Frame Counter*	*Report Value*
Data Field	0,1='10'	2	3='0'	4='0'	5,6,7='000'	8-15

Figure 10. PLCW Structure

– Retransmit Flag, bit 2, is always '0' in transmission and don't care in reception. According to the standard, this flag should be set to '1' when retransmission is required for any of the previously receive frames. In the Odyssey implementation the need for retransmission is inferred from the Report Value field (see below)

– Virtual Channel ID field, bit 3, is always '0' (no support for multiple VCs) in transmission, don't care in reception

– Expedited Frame Counter is always set to '000' in transmission (counter is not implemented), don't care in reception

– Report Value Field, 8 bits, contains the next expected frame sequence number (0-255).

3.1.3 Sequence Controlled Service (Reliable Bit Stream Mode)

The sequence controlled service ensures the error-free transmission of the input bit stream to the receiving end, utilizing the frame layer structure described in the previous section. This mode is also called Reliable Bit Stream.

The serial data from the transceiver buffer is formatted in the data field of the frame. It must be noted that the Orbiter transmit a fixed length frame during a session as it will explained later in the paragraph. The bits 2 and 3 of the header, Figure 9, are set to '00' to indicate a sequence controlled frame:

- the Frame Sequence Number (last eight bits of the header) field will permit at the receiving end to verify that the packet is received in proper order. Since the counter has to be synchronized between the orbiter and lander a flight rule[13] specifies that before every communications pass the orbiter UHF transceiver will be powered on and off. This will reset the orbiter frame counter to zero and an action with the same effect has to be taken by the surface element

- the 32 bits CRC appended after the frame will allow the receiver at the opposite end of the link to check if any bit of the packet suffered an error during transmission. If no errors are detected a PLCW frame will be returned in the opposite link indicating the next expected sequence number (Report Value field) incremented by one, otherwise the sequence number will stay the same. PLCW have higher priority than transfer frames containing data.

The orbiter transceiver inserts one byte of pad after each frame is transmitted. This byte is not envisioned in the Proximity standard and does not have to be implemented by the Surface Element transceiver.

In the sequence controlled mode the orbiter implements a Go-Back-2 ARQ (Automatic Repeat Request) protocol, which permits transmission of the next sequenced frame while receiving the PLCW for the one previously sent. In this way the throughput is increased respect to a Stop and Wait protocol. In the case where an ACK is not received before the end of the transmission of the second frame, the orbiter will keep sending the two transfer frames still to be acknowledged.

When asymmetrical full duplex communication is in place, the length of frame transmitted by the orbiter is restricted automatically as described in Table 4; based on the data rate of the forward and return link, the orbiter will transmit transfer frames with one the following number of bytes: 9, 42, 107, 238, 499, 1024[14].

Table 4. Length of Transfer Frame Transmitted by the Orbiter versus bit rate in the two directions

Forward Bit	Return Bit Rate	Forward Frame

[13] Flight Rule 0709-E-TELE, Project Document MSP01-99-0153, April 2000.
[14] If the transceiver buffer has less than the required number of bytes, a shorter frame will be sent.

Rate [kbps]	[kbps]	Length [bytes]
8	8	1024
8	32	238
8	128	42
8	256	9
32	8	1024
32	32	1024
32	128	238
32	256	107
128	8	1024
128	32	1024
128	128	1024
128	256	499
256	8	1024
256	32	1024
256	128	1024
256	256	1024

This is done in order to keep a balance in the Go-back 2 ARQ scheme between transmitted packets and return PLCW, as is shown in Table 5.

The time in seconds to transmit a transfer frame and a PLCW is given by

$$(L_{frame} + L_{CRC} + L_{ASM} + L_{PLCW} + 2)*8/R_b$$

where L_{CRC}=4, L_{CRC}=3, L_{PLCW}=14, L_{frame} is the frame length in bytes (including the header), 2 bytes are added to account the padding and R_b is the data rate in bits per second.

In Table 5, the assumption is that the fastest of the two links is sending frame 1024 bytes long, which is the maximum length that the orbiter transceiver can handle. The selection of the frame size in Table 5 assures that the duration to transmit one protocol unit with user's data (including overhead) and one PLCW is approximately the same in the forward and in the return directions. The throughput and efficiency shown in the table is also based on the assumption that no retransmission is taking place and that the SE is inserting one byte of pad between frames.

The transmission from the SE of different frame sizes (up to 1024 bytes) is allowed, but this size will influence the throughput of the two links. Hence when information is transmitted in both direction the efficiency of the link is under control of the Surface Element. In general the link that is taking less time to send a complete transfer frame will be less efficient because the other link is not able to acknowledge correct reception of frames fast enough.

When receiving only in the sequence controlled service, no data is sent in the forward link but the transceiver will insert idle bits between PLCWs.

Table 5. Effective Data Rate for Full Duplex Communication - No Retransmissions

Forward Link					Return Link				
Bit Rate	**Frame Length (*)**	**Time to TX frame + PLCW**	**Effective Bit Rate**	**efficiency**	**Bit Rate**	**Frame Length (**)**	**Time to TX frame +PLCW (***)**	**Effective Bit Rate**	**efficiency**
bps	**bytes**	**s**	**bps**		**bps**	**bytes**	**s**	**bps**	
8000	1024	1.047000	7787	**97.3%**	**8000**	1024	1.047000	7787	**97.3%**
8000	238	0.261000	7158	**89.5%**	**32000**	1024	0.261750	31148	**97.3%**
8000	42	0.065000	4800	**60.0%**	**128000**	1024	0.065438	124593	**97.3%**
8000	9	0.032000	1946	**24.3%**	**256000**	1024	0.032719	249186	**97.3%**
32000	1024	0.261750	31148	**97.3%**	**8000**	238	0.261000	7158	**89.5%**
32000	1024	0.261750	31148	**97.3%**	**32000**	1024	0.261750	31148	**97.3%**
32000	238	0.065250	28632	**89.5%**	**128000**	1024	0.065438	124593	**97.3%**
32000	107	0.032500	25363	**79.3%**	**256000**	1024	0.032719	249186	**97.3%**
128000	1024	0.065438	124593	**97.3%**	**8000**	42	0.065000	4800	**60.0%**
128000	1024	0.065438	124593	**97.3%**	**32000**	238	0.065250	28632	**89.5%**
128000	1024	0.065438	124593	**97.3%**	**128000**	1024	0.065438	124593	**97.3%**
128000	499	0.032625	121199	**94.7%**	**256000**	1024	0.032719	249186	**97.3%**
256000	1024	0.032719	249186	**97.3%**	**8000**	9	0.032000	1946	**24.3%**
256000	1024	0.032719	249186	**97.3%**	**32000**	107	0.032500	25363	**79.3%**
256000	1024	0.032719	249186	**97.3%**	**128000**	499	0.032625	121199	**94.7%**
256000	1024	0.032719	249186	**97.3%**	**256000**	1024	0.032719	249186	**97.3%**

(*) pre-programmed in the MSP'01 Transceiver based on forward and return bit rates
(**) SE Transceiver can transmit a variable frame length up to 1024 bytes
but the data length in this coloumn provides maximum efficiency
(***) assumes that the SE transceiver insert 1 byte of pad after each frame

3.1.4 Expedited Transfer Service (Message By-pass)

This mode was envisioned to have the feasibility of implementing, outside the transceiver, more sophisticated ARQ protocols than the Go-Back 2. It's indicated by the combination of the fields QoS and PDU Type ID equal to '10' (see Table 1).

When the orbiter transmitter portion is set into this mode, the transceiver looks into his buffer for the ASM of the Proximity-1 transfer frames then it looks for the header and captures a number of bytes corresponding to the Frame Length field and calculates and appends the CRC. Since the orbiter flight computer is not able to create Proximity-1 frames, the only option is to send them directly from ground as the content of the command data flow. The QoS indicator in the header should be set to '1' indicating that at the receiver end the sequence number check should not be performed. PLCW received in this mode are ignored since the transceiver does not retain the transmitted frames in its buffer.

When receiving frames indicating expedited service, the frame is subject only to CRC check, not to sequence number and SCID checks. Note that even in this mode the orbiter radio responds with a PLCW, but the Report Value field is indicating frame sequence number of the sequence controlled service and the expedited frame counter is always zero, so that the only useful information is that a frame did or did not pass the CRC check.

3.1.5 Link Establishment Sequence

The frame layer protocol will be used for establishing a link between the orbiter and the Surface Element and the link is always initiated by the orbiter.

When commanded to, the orbiter will transmit at 8 kbps a Directive PDU with a Set Transmit and Set Receive directives in order to configure the transceivers at both ends in a compatible mode. The

Directive PDU can be sent independently from the quality of the service (service controlled, expedited or unreliable bit stream mode) selected.

The transceiver can select 3 methods for link establishment:

1. PSK Command Beacon - link establishment with PSK modulation
2. FSK Command Beacon - link establishment with FSK modulation
3. Disable Command Beacon - the Directive PDU is not sent; the transceivers at the two ends of the links have to be set in a compatible mode by the respective flight computers.

Irrespective of the content of the Set RX Directive, the orbiter will transmit the Directive PDU always uncoded at a data rate of 8 kbps.

In the case of PSK command beacon, see Figure 12, the orbiter will transmit a Carrier only signal lead (Continuous Wave, CW) for about 1 s to aid carrier acquisition. Then an Idle-pattern (alternating '1' and '0') is transmitted at 8 kbps in order to aid the bit synchronization at the receiver. This sequence is 4096 bits long for PSK. Then the orbiter transmit the Set Transmit and Set Receive Directives (the Directive PDU of Figure 9, consisting of 17 bytes including the ASM, the header and CRC that will take 17 ms at 8 kbps).

At this point the orbiter will switch its transmission to the data rate contained in the Set Receiver directive and send another second of CW followed by 4096 bits of idle-pattern. This is followed by either a transfer frame if there are command data to send or by an idle pattern. The orbiter waits for a response for a total of 2 s starting with the transmission of the second CW: if no response is received the transmitter cycles off for 2 s and then repeats the hailing sequence until the link is established or the orbiter transceiver is commanded to a different mode. If the orbiter receives a response from the lander in those 2 s the link is established.

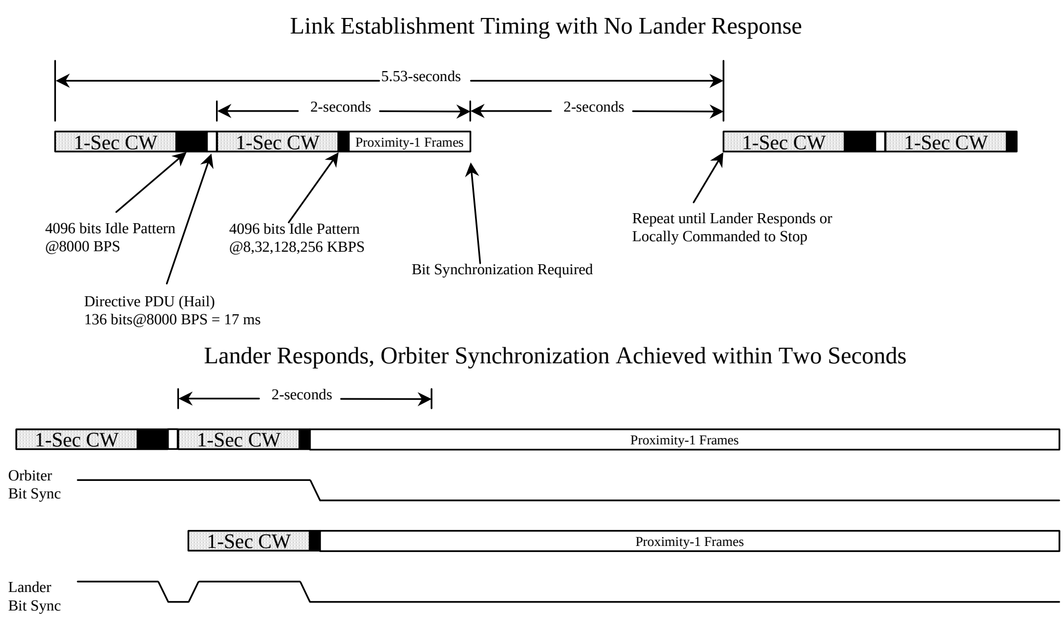

Figure 11. Link Establishment Timeline with Orbiter Transmitting and SE Transmitting PSK modulation

The use of FSK command beacon for the link establishment follows the same timeline, but it does not require the CW lead and its idle pattern is 512 bits long instead of 4096 bits.

If the link is lost during a pass (that is if the bit synchronization is lost) the link establishment sequence detailed above will start again, as long as the transceiver is not set to Disable Command Beacon.

Table 5 summarizes the timeline for PSK and FSK link establishment in the case where the forward link is always maintained at 8 kbps and no response is received from the SE.

Table 6. Timeline for Link Establishment

Time Interval	Duration (ms) PSK case	Duration (ms) FSK case
CW	1000	0
Idle-Ready	512 (4096 bits)	64 (512 bits)
Hail PDU	17 (136 bits)	17 (136 bits)
CW	1000	0
Idle Ready	512 (4096 bits)	64 (512 bits)
Idle-Tail of Data	488	1936
Transmitter Off	2000	2000
Total Time	**5.529 seconds**	**4.081 seconds**

3.2 Additional Services

3.2.1 Unreliable Bit Stream Mode

The UHF Transceiver can be set to unreliable mode independently for its receiver and transmitter portions. In this mode the frame layer protocol described in Sec. 3.1.2 is not used , but the Set directive can still be sent to establish the link.

When the orbiter is set to transmit the radio will simply transmits data continuously when the transceiver buffer is not empty (at least one byte is present) assuming that the radio at the other end is in a compatible mode. The transceiver does not wrap the data in Proximity-1 transfer frames. Prior to data transmission 1 s CW (PSK transmission only) and the bit sync preamble (4096 bits for PSK, 512 bits for FSK) will be sent by the radio. Transmission will stop when the FIFO buffer is empty or the transceiver is commanded in a different mode. The transmitter will cycle on and off based on the presence or not of data in the transmit buffer of the transceiver.

When the orbiter radio is set to receive in unreliable bit stream mode, the received data (demodulated and optionally decoded) will be output directly without buffering to the Telemetry Relay Buffer via the ULDL card.

Operational scenarios for using this mode have yet to be developed.

3.2.2 Canister Mode

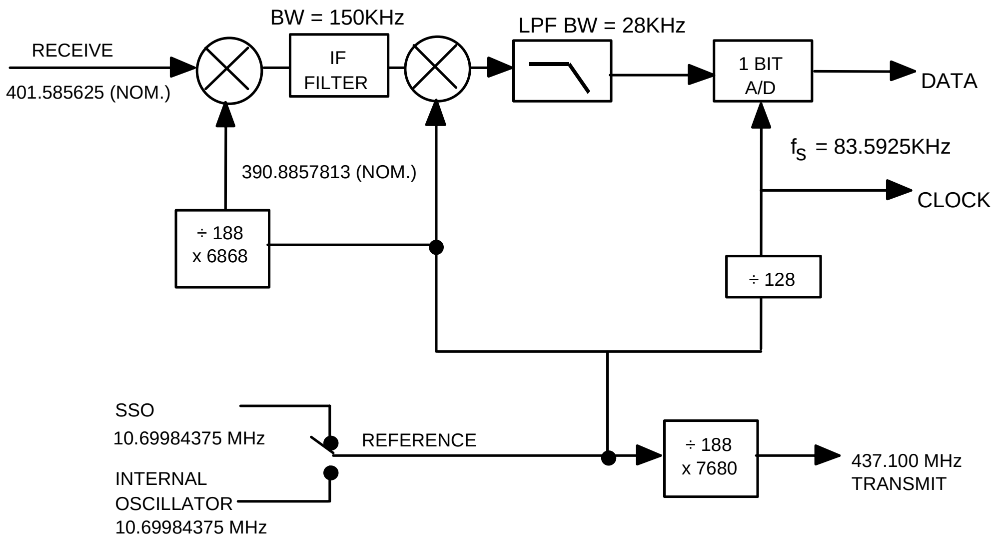

Figure 12. Canister Mode Functional Block Diagram

Canister mode allows the processing of very low power signal received by the orbiter at 401.585625 MHz with an open loop. This processing capability is limited to sampling at 83.6 kHz and digitizing with 1 bit accuracy of the baseband signal. This mode is enabled by a discrete strobe asserted by the C&DH to start canister data collection.

The reference for the downconversion and for the sampling clock can be either derived from the oscillator internal to the transceiver or from a more stable external reference called Sufficiently Stable Oscillator (SSO). See Section 3.3 for specifications on the oscillator performance.

The received signal downconverted, sampled and digitized is then sent out to the flight computer through the data interface. The canister data is inserted in fixed-length packets with APID (Application Packet ID) 35.

The format of the Canister data packets is as follows:

– Strobe ENABLED Time (Seconds), 4 bytes, 32-bit unsigned integer indicating the second portion of the SCLK time at the enabling of the strobe
– Strobe ENABLED Time (Subseconds), 2 bytes, 16-bit unsigned integer indicating the subsecond portion of the SCLK time at the enabling of the strobe
– Raw RF Data, 2182 bytes containing the 1-bit samples of the received signal.

Due to flight software constraints, the precision of the time-stamp is 20 ms. The canister data packets will be inserted in the normal telemetry transfer frames stream and sent to the ground for post-processing.

3.2.3 Tone Beacon Mode

Tone beacon mode offers for the following CW (pure tones) frequencies:

- 437.1000 MHz
- 440.7425 MHz
- 444.3850 MHz
- 448.0275 MHz

These tones can be used to trigger transmission from up to 4 different microprobes. Microprobes can that transmit in a pre-determined configuration compatible with the orbiter receiving mode.

The 437.1 MHz tone can also be used to perform 2-way Doppler measurement with a SE without sending commands from the Orbiter.

3.2.4 Doppler Measurement Service

The Doppler measurement on the incoming signal can be performed when the orbiter transceiver is configure is a PSK receive mode and the carrier lock is achieved. In addition Doppler collection is enabled by a strobe.

Refer to the block diagram of Figure 13 for the following explanation of the Doppler measurement.

The incoming frequency is phase locked by the PLL oscillator (a TCVCXO, so the TCVCXO frequency is coherent with the incoming frequency with the ratio of 188/7056.

The TCVCXO frequency is beat note mixed with the reference frequency resulting in a beat note at the difference of the frequencies. Note that the reference can be derived from the oscillator internal to the transceiver or from the more stable SSO. The beat note is counted over an interval which is approximately 5 seconds. Simultaneous with counting the beat note, a time counter counts the number of reference frequency cycles. The interval always starts on a zero crossing of the beat note and always ends on a zero crossing of the beat note.

The first interval begins on the first beat note zero crossing after the strobe discrete input has been activated. The two counters are never reset except before the first interval (i.e. cleared by the Doppler strobe rising edge). At the end of any interval both the zero crossing counter and time counter are snapshot (captured in a register) and sent to the spacecraft. The counters continue counting since the end of one interval is always the start of the next. The counters are therefore modulo with the zero crossing counter being 11 bits and the time counter being 26 bits.

The following is an example of the process:

1)The incoming frequency is exactly 401.585625MHz + 1,000.000 Hz.

2)The locked frequency of the TCVCXO is 10.6998703939909 MHz (401.586625MHz *188/7056).

3)The beat note frequency is 10.699843750MHz (externally supplied USO reference) – 10.6998703939909MHz (TCVCXO)=26.6439909283071Hz

4)Over a 5 second period the beat note will have covered 133.219… cycles. Since the interval can only end on a zero crossing the interval becomes 134 cycles (next whole number of cycles).

5)134 cycles at 26.6439… Hz is 5.02927659600857 seconds.

6)An interval of 5.029… seconds results in 53,812,473 reference counts.

7)The captured counter values sent to the spacecraft would be 134 (+last intervals zero crossing counter since it doesn't reset) in the zero crossing counter and 53,812,473 (+last interval time counter since it doesn't reset) in the time counter.

8)To reconstruct the incoming frequency on earth take the interval time of 5.0292765256502 sec (calculated by taking the time count of 53,812,473/Reference Frequency) and divide it into the zero crossing number of 134. This results in 26.6439913010502Hz. Take this and add to the reference frequency and convert back to the front end frequency by multiplying by 7056 and dividing by 188. [(26.64…+10.69984375Mhz)*7056/188)]. This yields 401.5866250000140 Mhz which is the front end frequency to within 14 microherz.

9)If I increase the frequency by a single milliherz the zero counter stays at 134 and the time counter becomes 53,812,419. This results in a calculated frequency of 401.586625001017 MHz which is accurate to the front end frequency to within 17 microherz.

As for canister data, Doppler measurements are inserted in fixed length packets (APID 34) with the following format:

- Strobe ENABLED Time (Seconds), 4 bytes, 32-bit unsigned integer indicating the second portion of the SCLK time at the enabling of the strobe
- Strobe ENABLED Time (Subseconds), 2 bytes, 16-bit unsigned integer indicating the subsecond portion of the SCLK time at the enabling of the strobe
- Doppler Data, 2182 bytes containing the Doppler data (zero cross counter and time counter) as described above.

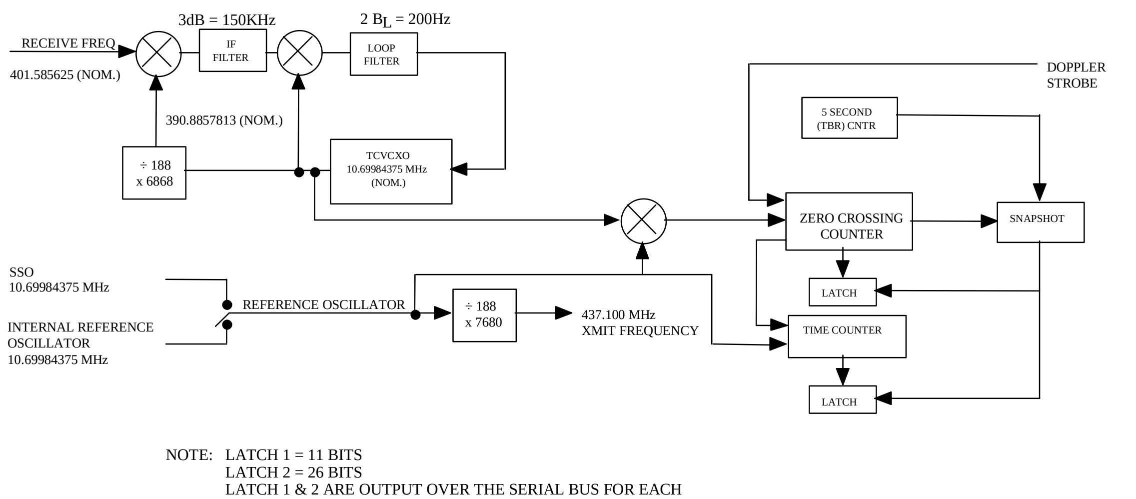

Figure 13. Doppler Functional Block Diagram

3.3 *Orbiter UHF Subsystem Description*

3.3.1 Block Diagram

Figure 15 shows the block diagram of the UHF subsystem implemented on the MSP'01 UHF subsystem.

The transceiver is the communication terminal for the relay link and it includes a power amplifier. The SSO (Sufficiently Stable Oscillator) provides increased frequency stability for the Doppler and canister services. The transceivers and the SSOs are block redundant, but there is no cross-strapping between the CD&H and the transceivers and between the transceivers and the SSOs. A single antenna will provide transmitting and receiving capability and a switch will connect it to the active UHF radio.

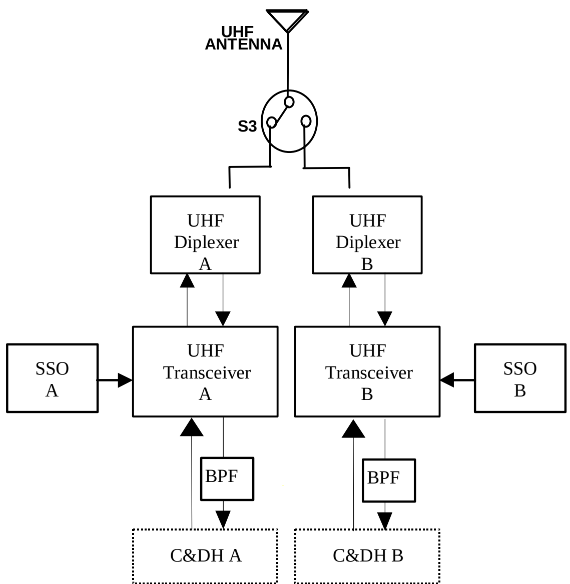

Figure 14. Block Diagram of UHF Subsystem

3.3.2 Antenna

The antenna for relay communications is a quadrifilar helix.

The antenna pattern is depicted in Figures 16. The measurements were taken with the flight antenna mounted on a mock-up of the spacecraft for the right hand and left hand polarizations. The solar arrays were not modeled by the mock-up.

In picture the distance from the center ($\sqrt{x^2 + y^2}$) represents the off-boresight angle in degrees, while the counter-clock-wise angle from the x axis ($\tan^{-1}(y/x)$) is the azimuthal cuts of the pattern measurement (where 0° is the S/C z-axis, GRS direction and 90° is the y-axis, solar arrays direction).

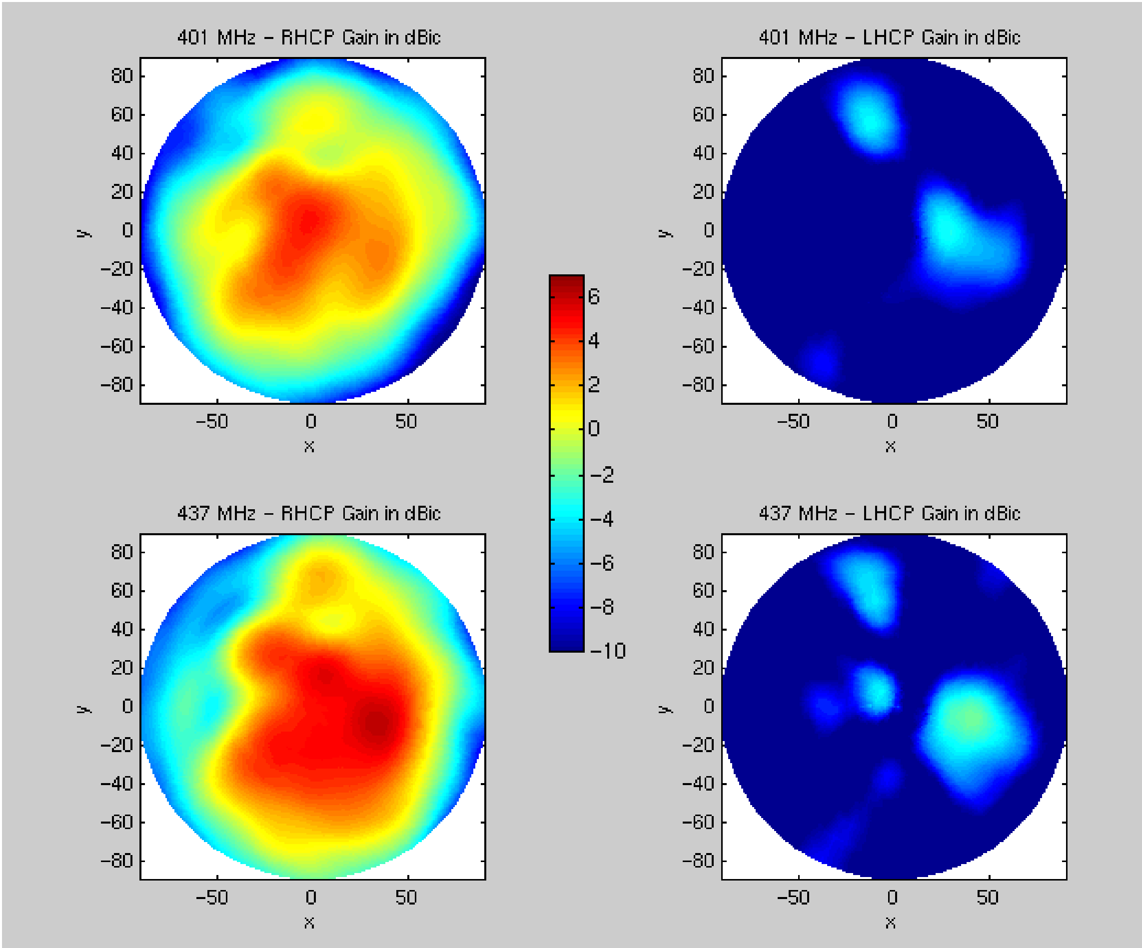

Figure 15. UHF Antenna Pattern as Measured on the Spacecraft Mock-up

The effect of the Solar Array (S/A) position on the UHF pattern has been analyzed with the GTD (Geometrical Theory of Diffraction) method and the results are illustrated in Figure 16 and Figure 17. Note that this picture also includes the effect on the 17° tilting of the spacecraft during the mapping-relay phase mission (see Appendix A for a description of the attitude). In other words the distance from the center of the pattern is the angle off Nadir, not off-boresight.

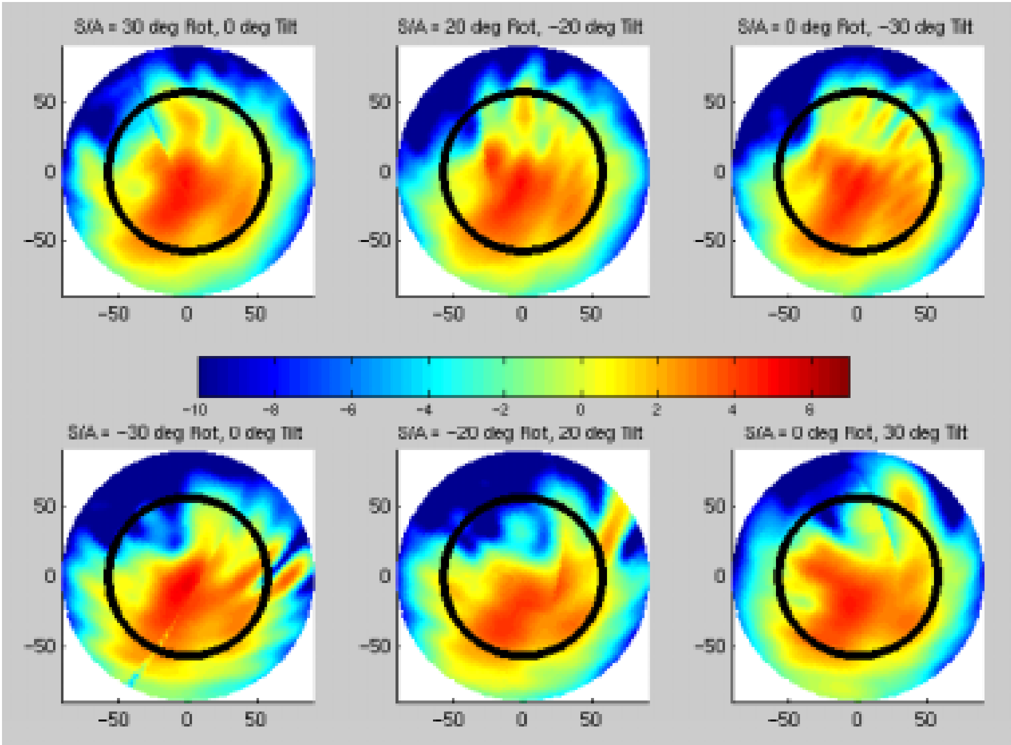

Figure 16. UHF Pattern at 402 MHz for different Solar Array (S/A) positions

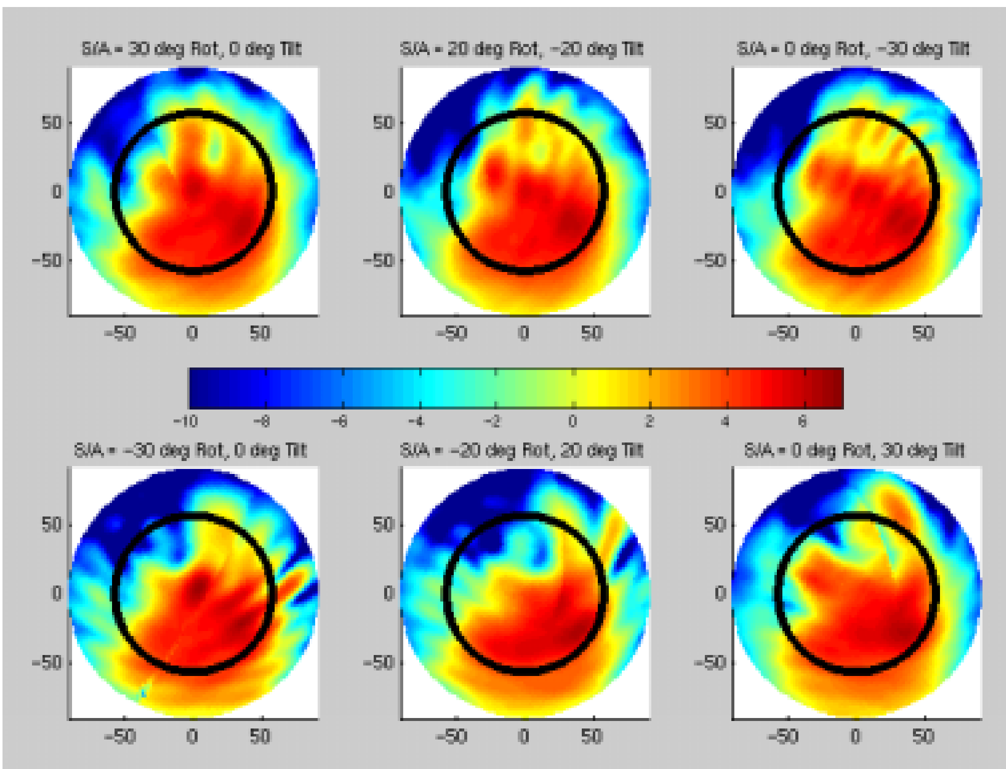

Figure 17. UHF Pattern at 437 MHz for different Solar Array (S/A) positions

3.3.3 Transceiver

The transceivers are manufactured by Cincinnati Electronics (CE). The two flight units were tested extensively during the acceptance test[15]: SN001 was tested at proto-flight levels while SN002 at flight acceptance levels. SN001 is Unit A in the UHF subsystem block diagram, while SN002 is Unit B.

The following Table summarizes the main specifications and the compliance of the two units: final refer to the set of tests conducted at room temperature after random-vibration and thermal cycling.

Table 7. Transceiver Compliance Matrix

Parameter	Specification	SN001 final	SN002 final
Noise Figure[16]	≤ 3 dB	2.5 dB	2.4 dB
RF Power[17]	≥ 40 dBm	41.1 dBm	41.4 dBm
Modulation Index	1.05±0.15 rad	1.1 rad	1.1 rad
Carrier Acquisition Time	≤ 1000 ms	224 ms	200 ms
Carrier Acq Threshold	≤ -123 dBm	-127 dBm	-130 dBm
Carrier Track Threshold.	≤ -123 dBm	-133 dBm	-133 dBm

The specification for the frequency range for carrier acquisition and tracking are ±8 kHz and ±12 kHz (at 100 Hz/s) respectively. During the thermal cycling the following non-compliance was noted (with an input power of -121 dBm):

Table 8. Acquisition performance - waiver for SN001 (proto-flight level testing)

spec	non-compliance	temperature
-8/8 kHz	-6.6 kHz	75 ^{o} C
-8/8 kHz	7.9 kHz	25 ^{o} C
-8/8 kHz	7.1 kHz	-50 ^{o} C

Table 9. Tracking performance - waiver for SN002 (flight acceptance level testing)

spec	non-compliance	temperature
-12/12 kHz	11.1 kHz	65 ^{o} C
-12/12 kHz	11.1 kHz	25 ^{o} C
-12/12 kHz	11.6 kHz	-40 ^{o} C

Given that predicted operational temperature during the relay phase will be between -19° C and +27° C, the project waived the requirement.

The specifications for the receiving thresholds for a Bit Error Rate (BER) of 1E-6 are contained in the following Table. When the Proximity-1 protocol is used the maximum frame size is 1024 bytes and

[15] Supplement Test Report on CE Model C/TT-505 SN001 and SN002, June 2000.
[16] Noise figure was measured at part level before acceptance tests.
[17] The RF power will vary with the transceiver temperature: it was measured to be about 0.2 dB lower at +65°C and 0.3 dB higher at -40°C.

information is output by the transceiver only if frames are received with no errors. Assuming independent errors the FER (Frame Error Rate) will be 8.1E-3 when the BER is 1E-6.

Table 10. Receiving Threshold vs. Bit Rate - Specifications

Bit Rate	FSK uncoded	BPSK coded
8 kbps	-109 dBm	-120.5 dBm
32 kbps	N/A	-115.5 dBm
128 kbps	-103 dBm	-109.5 dBm
256 kbps	N/A	-106.5 dBm

During BER measurements a test set (not an other Transceiver unit) was used to generate an RF signal with BPSK modulation and a modulation index of 1.05 rad (60°). In addition since the diplexer was not available in June, the receiving thresholds wheretested with the transmitter off.

Figure 18 shows the BER for PSK versus the power at the input of the Transceiver (Pt).

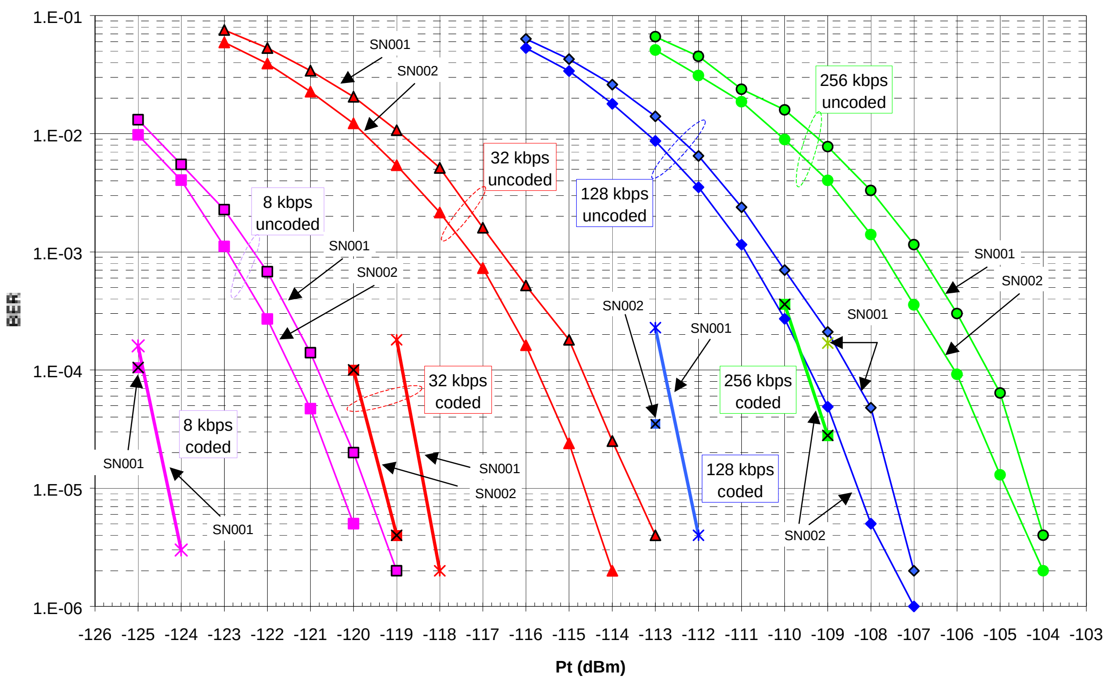

Figure 18. BER vs. Received Input Power for BPSK

Figure 19 and Figure 20 present the same results plotting BER versus Eb/No, where Eb/No is calculated as follows:

$$Eb/No\ (dB) = Pt\ (dBm) + 174\ (dBm/Hz) - NF(dB) - 1.25\ (dB) - Rb\ (dB\text{-}Hz)$$

where NF is the noise figure (2.4 dB for SN102, 2.5 dB for SN101) and -174 dBm/Hz is the noise floor with the room temperature of 290°K. The suppression of 1.25 dB is due to the modulation index of 60° and Rb is the data rate.

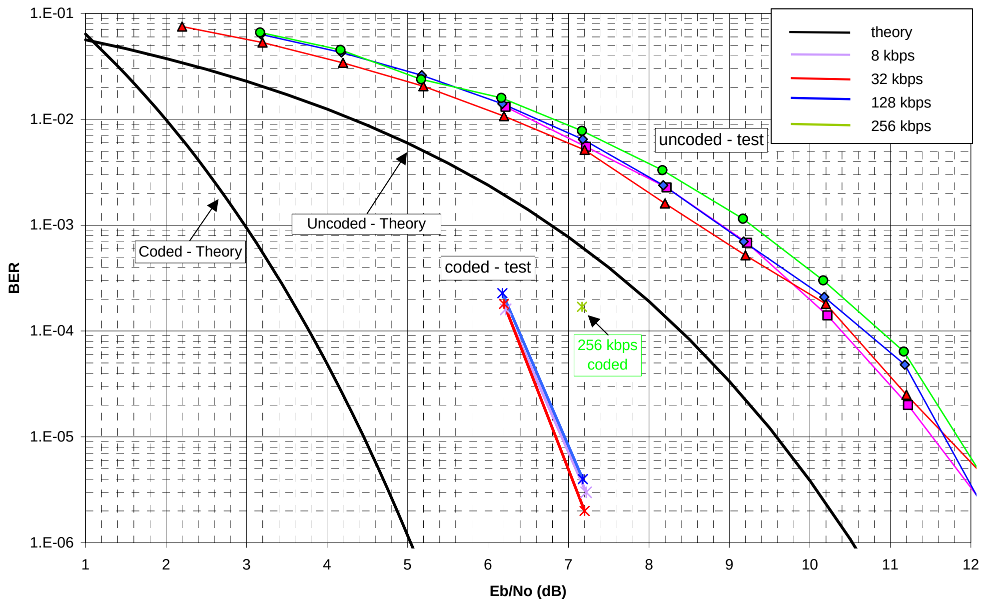

Figure 19. BER vs. Eb/No - SN001 - BPSK

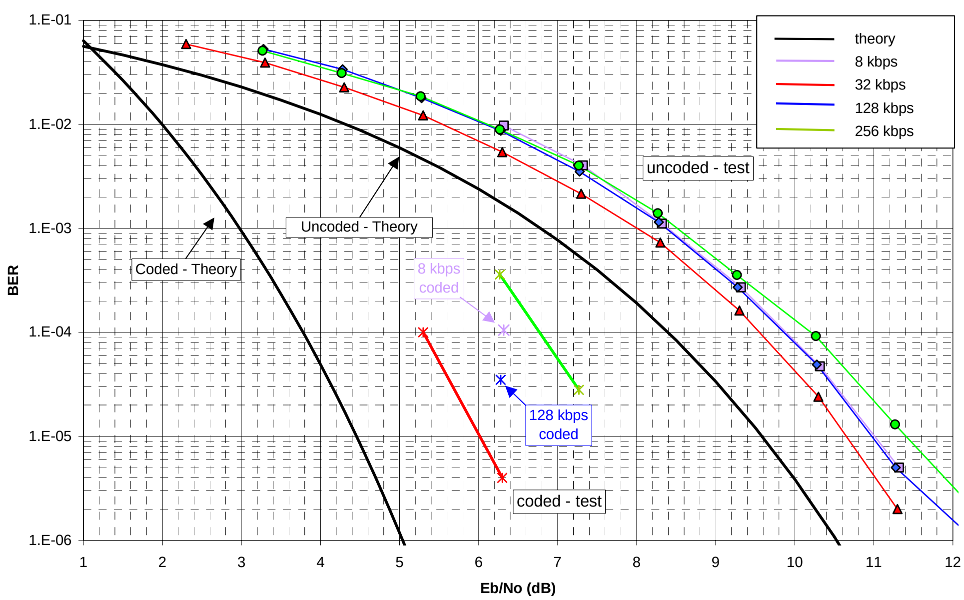

Figure 20. BER vs. Eb/No - SN002 - BPSK

The transceivers were tested again at Cincinnati Electronics in January 2001 with the flight diplexers and additional data were collected to characterize the performance for BPSK coded reception at 32 and 128 kbps that were perceived as most important for future missions. A comparison with the ATP data is shown in Figure 21. Note that in this case side A and B refer to the block redundant UHF string of Figure 14, where Transceiver A is S/N 001 and B is S/N 002. Figure 22 shows the BER vs. input power for FSK.

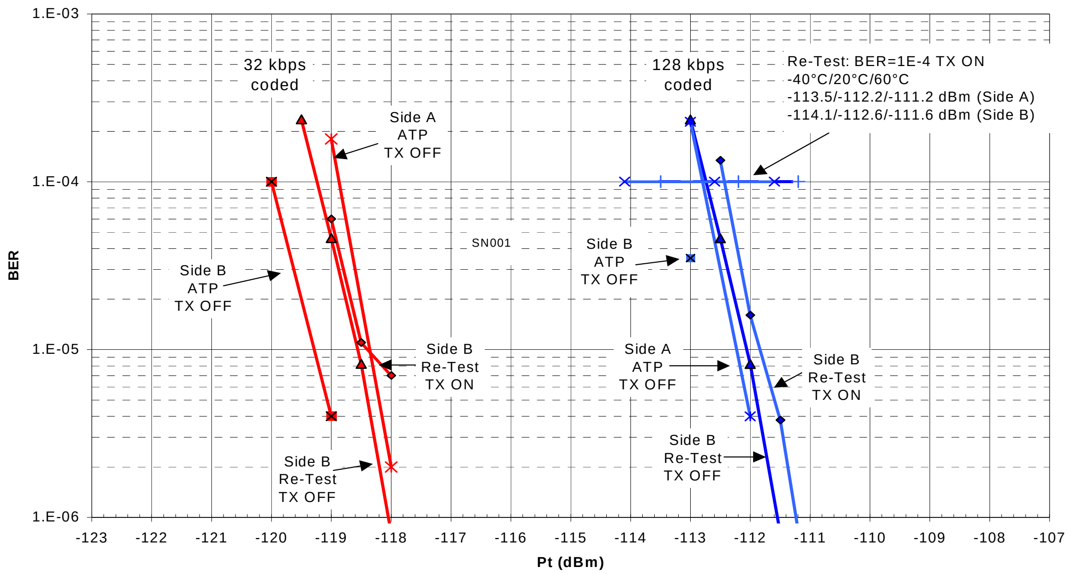

Figure 21. BER vs. Received Power for BPSK coded

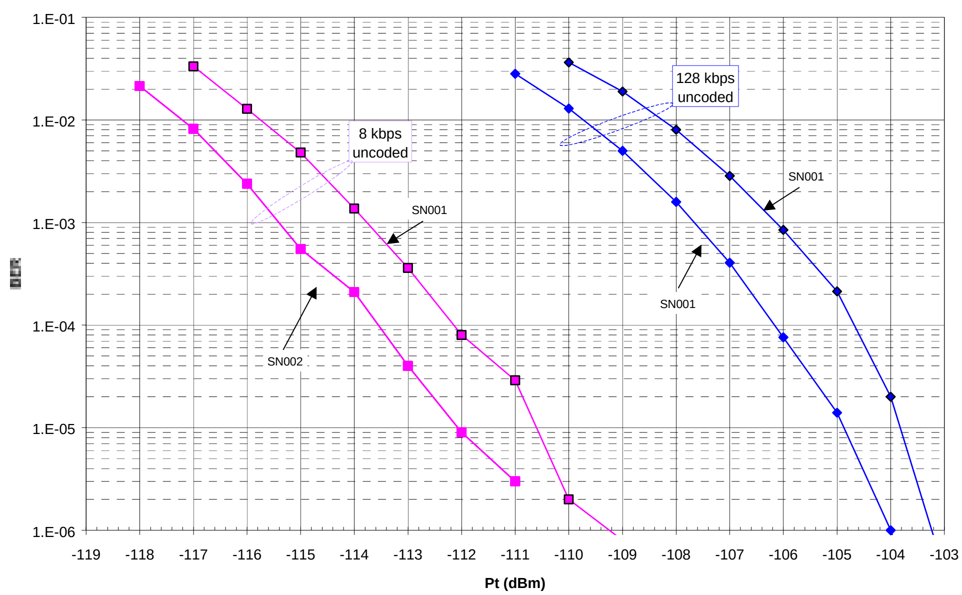

Figure 22. BER vs. Received Input Power for FSK

During operations in Mars orbit, the threshold at the input of the transceivers required for a given BER will be lower than what is shown in Figures 18, 21 and 22. This is due to the fact that while the required Eb/No will stay the same, the system noise temperature will be lower in Mars Orbit. It can be shown that the system noise temperature is given by

$$T_{\text{flight}} = T_a 10^{\frac{L}{10}} + T_p\left(10^{\frac{NF}{10}} - 10^{\frac{L}{10}}\right)$$

where T_a is the temperature received by the antenna, L is the circuit loss (in dB and negative) between the antenna and the transceiver, T_p is the device temperature assumed at 290°K and NF is the noise figure of the transceiver. Even assuming that the antenna collects the 210° of the Mars surface temperature and using NF=2.5 dB and L=-1.8 dB (see Sec 3.3.5), T_{flight}=463 K which is 0.5 dB lower than the system noise temperature during ground test

$$T_{\text{test}} = T_p 10^{\frac{NF}{10}} = 516\,\text{K}$$

During system test in December 2000, the degradation in the transceiver thresholds due to EMI from the spacecraft was assessed. Since BER measurements were not possible, carrier and other lock indicators were used. It was found that in average there was a degradation of 2 dB for the 8 and 32 kbps data rates, and of 3 dB for the 128 and 256 kbps data rates. Due to the type and quality of these measurements the degradation is still questionable, but users are advised to allow 3 dB for EMI in the return link budget. A test is planned in June 2001 to characterize the performance with EMI in flight conditions, sending an uplink at UHF from the Stanford antenna.

The oscillator internal to the Transceiver is a Temperature Controlled TCXO. The variation over temperature of the output frequency (around 437.1 MHz) was measured and the results are presented in Figure 23. The internal oscillator meets the 2 ppm specifications.

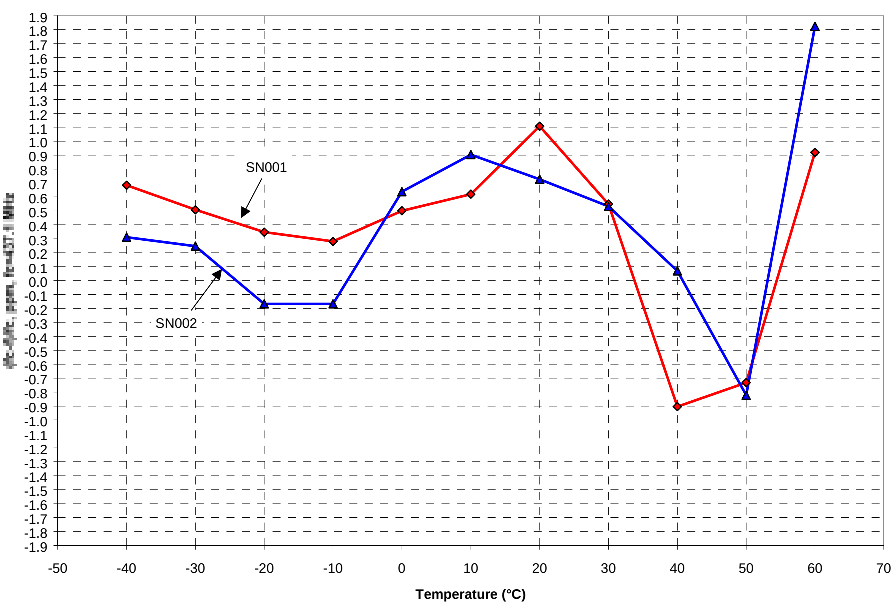

Figure 23. Variation of Output Frequency with Temperature

Finally it was verified by analysis that the Transceiver warm-up time (to reach full compliance to the specifications) is below 60 ms.

3.3.4 Sufficiently Stable Oscillator

The following are the test results made on March 2000 for the Sufficiently Stable Oscillator (SSO) at the reference frequency of 10.69984375 MHz.

Table 11. Phase Noise vs. Frequency Offset from Carrier

Offset from carrier Hz	Specification dBc/Hz	S/N 1581554 dBc/Hz	S/N 1581555 dBc/Hz
1	-90	-96[18]	-96[15]
10	-120	-130	-131
100	-145	-148	-145
1000	-155	-157	-157
10000	-160	-165	-167

Table 12. Allan Deviation vs. integration time

Integration Time seconds	specification	S/N 1581554	S/N 1581555	comments
1	1.0E-11	4.8E-12	4.9E-12	pass
10	1.0E-11	2.0E-12	1.9E-12	pass
100	1.0E-11	2.5E-12	2.7E-12	pass
1000	1.0E-11	4.6E-12	2.1E-11	waiver for S/N 1581555

[18] Measured on breadboard SSO.

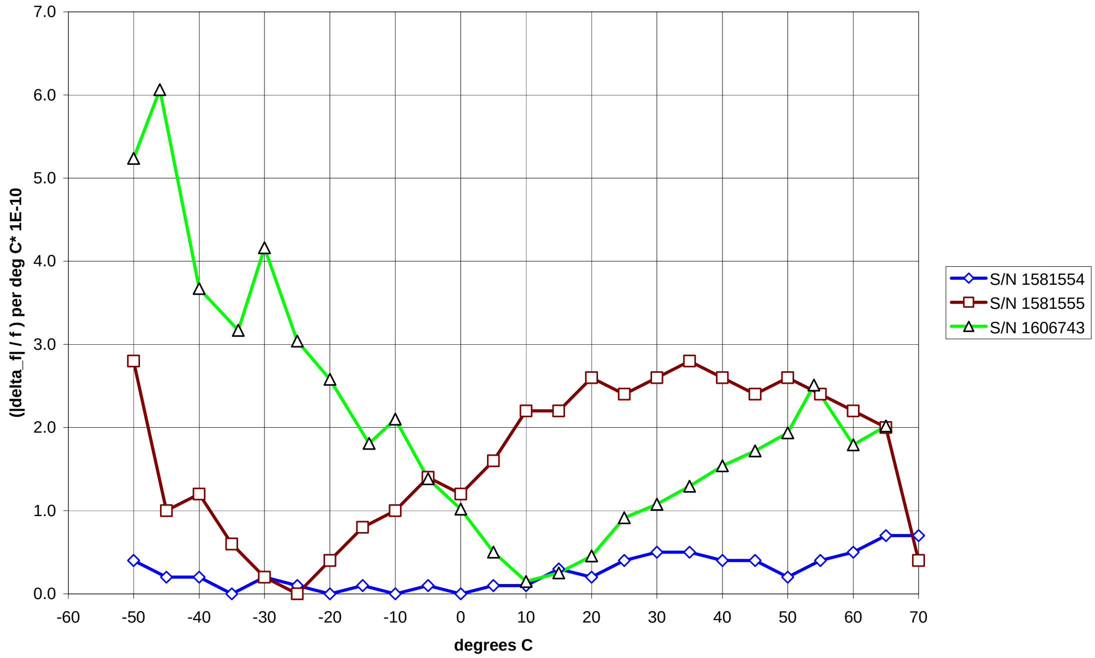

Figure 24. SSO frequency Stability vs. Temperature, delta_f/f per °C, Vectron test data

3.3.5 Circuit Loss

The following Table summarizes the current best estimate for the circuit losses between the orbiter transceivers RF output and the antenna.

Table 13. Circuit Loss

link / direction	elements	value
UHF / transmit	Transceiver A to Antenna	1.0 dB
UHF / transmit	Transceiver A to Antenna	0.9 dB
UHF / receive	Antenna to Transceiver A	1.8 dB
UHF / receive	Antenna to Transceiver B	1.7 dB

Appendix A: Orbital Elements and Orbiter Attitude

Table 14 lists the Nearly Sun-synchronous orbits[19] at Mars that will support mission after 2003. Nominally the orbiter will be in a circular orbit 400 km above the surface.

Table 14. Mean Orbital Elements during Nearly Sun Synchronous Orbit

Parameter	**Value**
Epoch	19-Oct-2003 00:00:00 ET
Semi-major axis	3793.4 km
Eccentricity	0.0
Inclination	93.064°
Argument of Periapsis	0.0°
Longitude of Ascending Node	34.98°
Mean Anomaly	0.0°

Figure 25 shows the orbiter attitude during the science phase with respect to the velocity and the nadir pointing vectors. Note that the orbiter is canted 17° over the velocity vector so the UHF antenna, along the -x axis, will be nominally pointed 17° off nadir.

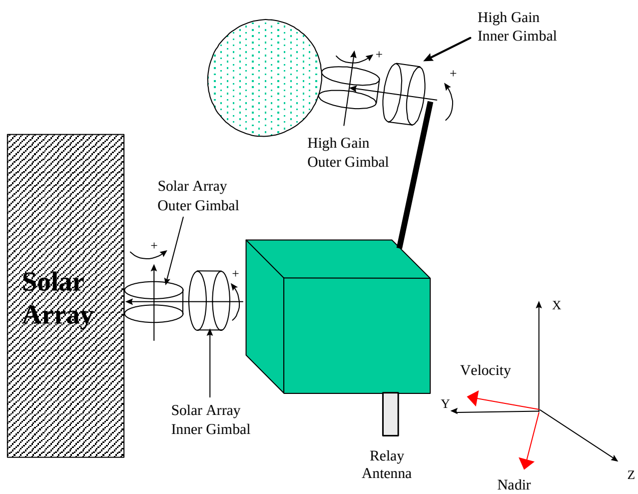

Figure 25. Spacecraft Attitude during Science and Relay Phase

[19] Navigation Plan and Trajectories Characteristics, MSP'01 Project Document 722-202, July 1999.

Appendix B: Overview of Orbiter Telemetry Transfer Frame

Variable-length packets are inserted by the flight software into fixed-size transfer frames according to the CCSDS standard[20]. The transfer frame is the data structures that provides efficient transport of packetized data in the deep-space link. Note that more than one packet can be inserted in a single transfer frame and that a single packet can span multiple transfer frames.

The structure of the transfer frame, illustrated in Figure 26, is composed by a header and a fixed size-data field. In the MSP'01 case the data field is 8752 bits long as is typical for most NASA deep space missions.

	Header	*Data Field*
bits	48	8752

	ASM	*Virtual fill*	*Transfer Frame*	*R-S*
bits	32	120	8800	1280

Logical Code-block = 10200 bits

	ASM	*Transfer Frame*	*R-S*
bits	32	8800	1280

Transmitted Code-block = 10080 bits

Figure 26. Telemetry Transfer Frame and Reed Solomon Code Block definitions

The transfer frame header is 48 bits long and is composed by the following fields:

- Version number: 2 bits ('00')
- Spacecraft Identifier: 10 bits with the value '35'h for the orbiter flight operations
- Virtual Channel (VC) ID: 3 bits ('000'- only one virtual channel supported)
- Operational Control Field Flag: 1 bits ('0'- operational control field not present)
- Master Channel Frame Count: 8 bits - sequential count (0-255) of each transfer frame
- Virtual Channel Frame Count: 8 bit - same as previous, since there is only one virtual channel
- Secondary Header Flag: 1 bit ('0'- no secondary header is present)
- Synchronization Flag: 1 bit ('0' - packets are placed contiguously on the frame and are coincident with octet boundaries)
- Packet Order Flag: 1 bit ('0' - forward sequence count)
- Segment Length Identifier: 2 bits ('11' - no segmentation)
- First Header Pointer: 11 bits - contains the location of the first packet in the transfer frame with a value of '0' indicating the first byte of the transfer frame.

[20] CCSDS Recommendation for Packet Telemetry 102.0-B-4, 1995. It can be obtained at http://www.ccsds.org/ccsds/publications.html#telemetry.

The concatenation of the header and the data field gives the transfer frame, which is 8800 bits (1100 bytes) long.

An attached Synchronization Marker (ASM) is inserted at the beginning of the frame. The ASM is specified as '1ACFFC1D'h. In addition the frame is protected by Reed Solomon encoding with an interleave depth of 5 adding 160 bytes of check-sum after the frame. On the ground this code will allow the correction of up to 80 byte errors.

The code is shortened from the standard (255,223) code to a (252,220) adding 120 bits of virtual fill. The virtual fill bits are pre-pended to the transfer frame so that the encoder will work on a block of data 8920 bits long (where 8920 is given by 255x8x5). These all-zero virtual fill bits are not transmitted and they will be inserted by the ground system before Reed Solomon decoding[21]. The code-block is the entity comprising the transfer frames and the Reed-Solomon check bits.

The total overhead due to the CCSDS frame structure for the orbiter is given by (32+48+1280)/(32+48+1280+8752)=13%.

[21] See CCSDS Telemetry Green Book, 100.0-G-1 Dec. 1987 P. B-3 for an explanation of the rationale behind the use of the virtual fill.

Appendix C: UHF Engineering Telemetry

1. UHF_PWR_SW1
   Indicates if Transceiver A is powered on [Open] or not [Close]
2. UHF_PWR_SW2
   Indicates if Transceiver B is powered on [Open] or not [Close]
3. UHF_CDHAUHFA
   Indicates if Side A [CD&H A and Transceiver A] is active [UHFA] or not [NOT_SEL]
4. UHF_CDHBUHFB
   Indicates if Side B [CD&H B and Transceiver B] is active [UHFB] or not [NOT_SEL]
5. UHF_RMODE
   Receiving Mode [STANDBY, REL_BIT_STR, MESSAGE_BYPASS, UNREL_BIT_ST, TONE_BEACON]
6. UHF_RECDR
   Receiving Bit Rate [8_KBPS, 32_KBPS, 128_KBPS, 256_KBPS]
7. UHF_RECMOD
   Receiving Modulation [FSK, PSK, PSK_coh]
8. UHF_RECCOD
   Receiving Decoding [SCRAMBLE, VITERBI_COD, BYPASS]
9. UHF_XMODE
   Transmitting Mode [STANDBY, REL_BIT_STR, MESSAGE_BYPASS, UNREL_BIT_ST, TONE_BEACON]
10. UHF_XMTDR
    Transmitting Bit Rate [8_KBPS, 32_KBPS, 128_KBPS, 256_KBPS]
11. UHF_XMTMOD
    Transmitting Modulation [FSK, PSK]
12. UHF_XMTCOD
    Transmitting Encoding [SCRAMBLE, VITERBI_COD?, BYPASS]
13. UHF_XMTBEC
    Modulation used for Link Establishment [DISABL_BEAC, FSK_BEACON, PSK_BEACON]
14. UHF_SCID
    Spacecraft ID of Surface Element
15. UHF_CCSDS_ST
    3-bits for each of the following counters:
    Transmit Advance Counter - incremented when ACK is received for a previously transmitted frame
    Transmit Restore Counter - incremented when a frame is retransmitted
    Receive Advance Counter - incremented when a received frame is accepted
    Receive Restore Counter - incremented each time a receiver frame is rejected
16. UR_ST_LKQ
    Link quality estimate from the bit sync
17. UR_BIT_SYN [Lock, No Lock]
    Indicates bit sync lock status
18. UR_CAR_LK [Lock, No Lock]
    Indicates carrier lock status
19. UR_VIT_LK [Lock, No Lock]
    Indicates Viterbi decode lock status
20. UHF_FIFO_SZ
    Size in Bytes of Transmitting FIFO in the transceiver
21. UHF_PA_TEMP
    Temperature (in °C) of the UHF Transceiver Power Amplifier

Appendix D: Acronyms List

APID	Application Packet ID
ARQ	Automatic Repeat Request
ASM	Attached Synchronization Marker
BER	Bit Error Rate
C&DH	Command & Data Handling
CE	Cincinnati Electronics
CCSDS	Consultative Comittee for Space Data Systems
CDU	Command Detector Unit
CRC	Cyclic Redundancy Code
CW	Continuous Wave
DSN	Deep Space Network
EDAC	Error Detection and Correction
EMI	Electro Magnetic Interference
FECW	Frame Error Control Word
FER	Frame Error Rate
FIFO	First In First Out
FSK	Frequency Shift Keying
GTD	Geometry Theory of Diffraction
LMA	Lockheed Martin Astronautics
LMTS	Local Mean Solar Time
MMO	Multi Mission Office
MSP	Mars Surveyor Project
NRZ	Non Return to Zero
PDU	Protocol Data Unit
PLCW	Proximity Link Control Word
PLTU	Proximity Link Transfer Unit
PSK	Phase Shift Keying
QoS	Quality of Service
RHCP	Right Hand Circular Polarization
RS	Reed Solomon
S/C	Spacecraft
SDST	Small Deep Space Transponder
SE	Surface Element
SN	Serial Number
SNR	Signal to Noise Ratio
SSO	Sufficiently Stable Oscillator
TBC	To Be Confirmed
TCXO	Temperature Controlled Crystal Oscillator
TMOD	Telecommunications and Mission Operations Directorate
UHF	Ultra High Frequency
ULDL	Uplink/Downlink
VC	Virtual Channel